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CATHODE RAY TUBE DISPLAYS

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NADC-88092-60

CONTENTS

	<u>Page</u>
FIGURES	v
TABLES	vi
PREFACE	vii
INTRODUCTION	1
HISTORY	1
HOW A CRT WORKS	1
PHYSICAL DESCRIPTION	1
BEAM DEFLECTION	3
DISPLAY SCREEN	4
HUMAN EYE	4
SPECTRAL RESPONSE	4
IMAGE RETENTION	4
CRT PHOSPHORS	5
PHOSPHOR EFFICIENCY	5
PHOSPHOR COLOR	6
PHOSPHOR PERSISTENCE	6
ELECTRON BEAM MOTION	6
RANDOM WRITING	6
RADIAL SCANNING	10
RASTER SCANNING	11
INTERLACED RASTER SCAN	11
INTENSITY MODULATION OF RASTER	12
COLOR CATHODE RAY TUBES	13
SHADOW MASK	13

NADC-88092-60

CONTENTS (continued)

	<u>Page</u>
PENETRON	15
BEAM-INDEX COLOR TUBE	15
OTHER COLOR TUBES	16
ESSENTIAL PERFORMANCE CHARACTERISTICS OF CRT'S	17
BRIGHTNESS	17
CONTRAST	19
GRAY SCALE	27
RESOLUTION	28
APPLICATION OF CRT DISPLAYS	37
OSCILLOSCOPES	37
RADAR	37
TELEVISION	37
INFORMATION DISPLAYS	38
SUMMARY	38
REFERENCES	39

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FIGURES

<u>Figure</u>		<u>Page</u>
1	Cathode Ray Tube as used in an Oscilloscope (A)Schematic View, (B)Pictorial View	2
2	Cut-Away View of Typical CRT Electron Gun and Deflection Plates	3
3	Relative Response Average Normal Eye	5
4	CRT Phosphor Spectra	7
5	CRT Phosphor Persistence	7
6(a)	Properties of Standard Phosphors	8
6(b)	Decay Time of Various Phosphors	9
7	Random-Write Scanning Mode	10
8	Pattern of Progressive Scan	11
9	Interlaced Scan Pattern	12
10	Shadow Mask Color CRT	13
11	Shadow mask CRTs (A) Delta gun arrangement with dot patterned phosphor, (B) In-line gun arrangement with stripe patterned phosphor	14
12	Schematic of Beam-Index Color Tube	17
13	Longitudinal Cross Section of CRT Showing Effect of Screen Curvature on Contrast.	21
14	Effect of Internal Reflection on CRT Contrast	21
15	Cross Section and Face View of CRT Screen Showing. How Total Internal Reflections Produce Halation	22
16	CRT with Conventional Powdered Phosphor Screen	24
17	CRT with Transparent Phosphor and Opaque Backing	26
18	Gray Shades, Relative Brightness, and Luminance Contrast	29
19	Brightness Range and Gray Shades in Familiar Scenes	29
20	Probability of Gap Detection	32
21	Image of line focused on Retinal Cones	33

FIGURES (Continued)

<u>Figure</u>		<u>Page</u>
22	Modulation Transfer Function (MTF)	36

TABLES

	<u>Page</u>
I Typical Luminances (In Footlamberts)*	18

NADC-88092-60

PREFACE

This report is meant to be useful to engineers having limited experience in electronic displays and to behavioral scientists working at the interface between electronic displays and human operators. It presents an overview of the technical fundamentals of cathode ray tubes and displays with some emphasis on elements and characteristics of interest to those in the human factors field.

Many excellent texts and a wealth of technical literature exist which treat these subjects in depth of detail more appropriate to the specialist or to those seeking more than a survey knowledge of cathode ray tube displays.

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INTRODUCTION

The Cathode Ray Tube (CRT) has been and still is the premier display device in the field of electronic display. This is true despite the enormous technical advancement in developing alternate methods and devices for alphanumeric and pictorial display. It is possible that some of these devices could, with further successful development, attain performance on a par with current CRTs. Indeed, some of them such as the Light-Emitting Diode (LED) matrix are being used for selected applications where their flat form is desirable and lower image quality can be tolerated.

HISTORY¹⁰

The earliest recorded scientific event that one might relate to the CRT occurred about 1603 when Casciorolo of Bologna, Italy, made a luminescent solid phosphor. Two centuries later, John William Hittorf of Munster, Germany, discovered that some type of cathode emission striking the glass wall of a glow tube caused the glass to luminesce. But it wasn't until 1875, in London, that Sir William Crookes assembled what could be called the first Cathode Ray Tube that produced luminance in a glass target. Crookes believed that cathode rays were electrified gas molecules, projected from the cathode, which produced luminescence when they struck the glass. Twenty-two years after the Crookes tube was demonstrated, Karl Braun of Strausberg, Germany, constructed the Braun tube with deflection and fluorescent screen, and used it as a display. This was in the year 1897, and the modern CRT is essentially a derivative of the Braun tube. An interesting fact of CRT chronology is that Sir Joseph John Thompson of Cambridge, England, identified the electron in 1897: the same year that Braun made his CRT. It wasn't until 1905 that Albert Einstein propounded the photon-quantum theory of light. At this point the CRT was developing ahead of the science that could explain its mechanism of operation.

The CRT was to become influential in both history and science. The Crookes tube had made the presence of electrons visible and x-rays were discovered from these electrons. Also J.J. Thompson used a CRT to measure the charge-to-mass ratio of an electron.

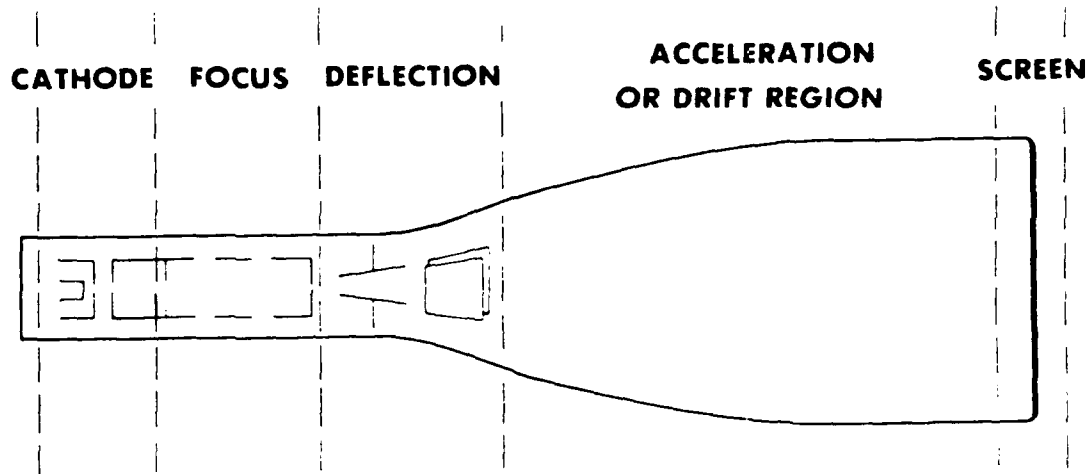
In World War II, the oscilloscope made radar a practical device which, among other achievements, was credited with breaking the German submarine blockade of Europe. CRTs are used in nearly all high speed measurements of atomic physics. The electronics industry would be helpless without the oscilloscope, and television, as a practical device, would not exist without the development of the CRT.

After the demonstration of television in 1926 and 1928 engineers steadily improved CRTs. Under the spur of mass commercial television, advancement of CRT technology accelerated and in 1950 A.C. Schroeder and A.N. Goldsmith of RCA Princeton Laboratories invented the shadow mask color tube. Many advances in allied fields of science and engineering are currently contributing to a continuous process of refining CRT performance.

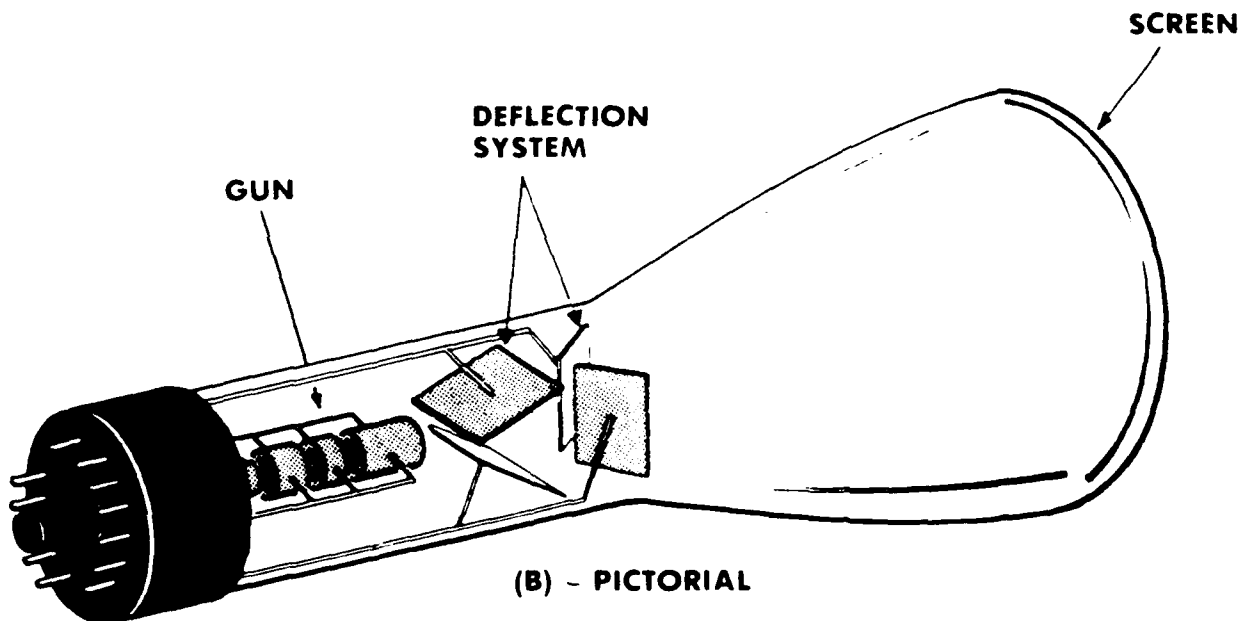
HOW A CRT WORKS

PHYSICAL DESCRIPTION

Essentially a CRT is an electron gun and a phosphor screen mounted in an evacuated glass envelope. These components are arranged so that an electron beam, generated and formed in the electron gun, can be directed onto the phosphor screen to produce a focused spot of light emission. The horizontal and vertical deflection electrodes in the electron gun can bend the electron beam, thus moving it over the phosphor screen. This enables the tube to create imagery in light which produces a "display". Figure 1(a) is a schematic portrayal of an elementary CRT.



(A) - Schematic



(B) - PICTORIAL

Figure 1. Cathode Ray Tube as Used in an Oscilloscope ^{1,2}
(A) Schematic View, (B) Pictorial View

The extreme left of Figure 1(A) shows the cathode. This component, which is heated to a high temperature by a tungsten filament, produces the electrons that are available to form an electron beam. As the electrons are accelerated to the right, they encounter focusing electrodes. These elements produce an equipotential electric field that has a focusing effect on the electron stream similar to the focusing effect of a refracting lens on light rays. The focused beam then enters the influence of horizontal and vertical deflection electrodes. The application of appropriate signal voltages to these electrodes deflect, displace, or bend the electron beam in accordance with signal variations. This causes the beam to traverse the phosphor screen in both horizontal and vertical directions resulting in the "writing" or "drawing" the desired image. Figure 2 is a cut-away perspective of an electron gun with electrostatic deflection electrodes.

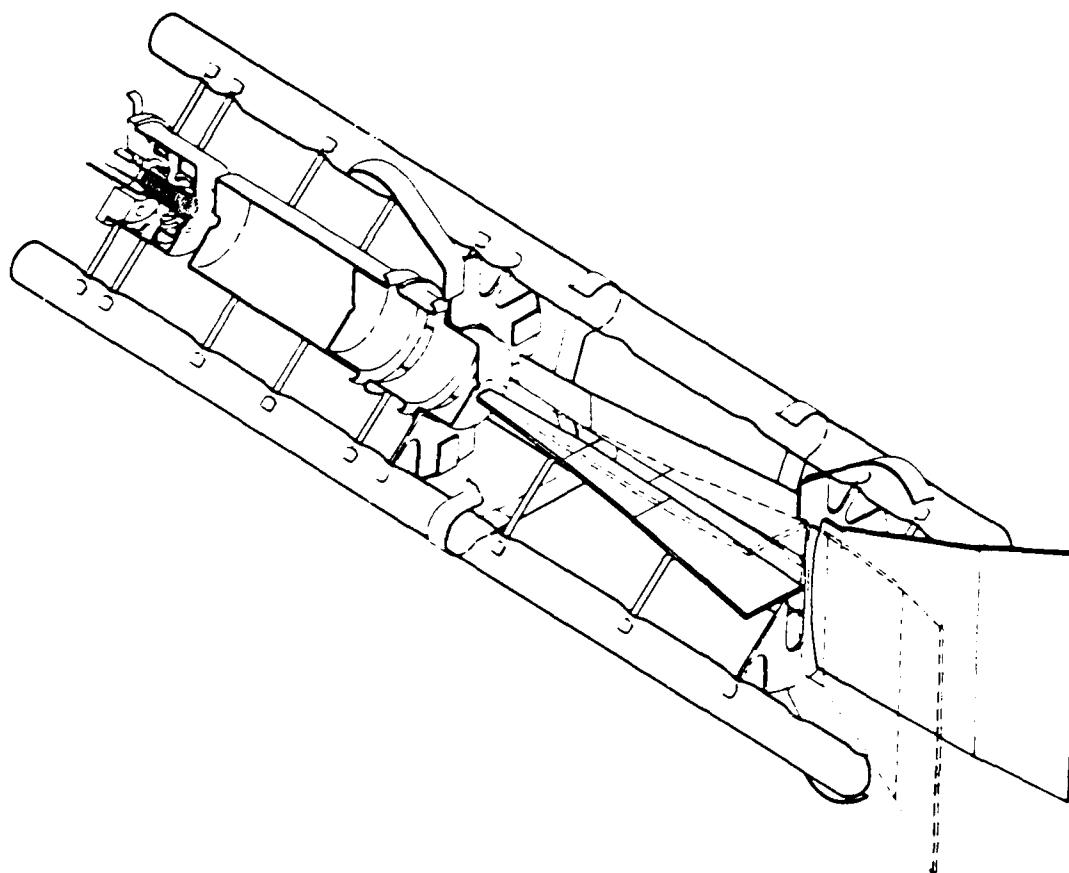


Figure 2. Cut-Away View of Typical CRT Electron Gun and Deflection Plates¹

BEAM DEFLECTION

The electron beam, that causes the spot of light emission on the phosphor screen, can be deflected by the application of either an electric field or a magnetic field. Electrostatic deflection has the inherent defect of defocusing the beam shape at large deflection angles. Deflection linearity is also degraded as the beam approaches the edges of the screen. The development of magnetic deflection solved both

NADC-88092-60

focusing and linearity problems, but at the cost of slower deflection speed, higher power requirements for large deflection angles, and increased heat dissipation in the deflection drivers and power supply.

In general, magnetic deflection tubes can focus the electron beam to smaller spot sizes at high luminances thus they have higher resolution. They produce greater brightness, and are capable of larger deflection angles. Their ability to deflect the beam at large angles make possible desirable reduction of tube length. On the other hand, electrostatic deflection tubes deflect the electron beam faster than magnetic deflection tubes by a factor of 10. They require less deflection power than magnetic deflection tubes saving weight and heat dissipation. They also have better resistance to physical shock due to the absence of heavy magnetic focus coils and deflection yokes which are mounted on the glass neck of the magnetic deflection tube. Potting the focus and deflection yokes with the CRT can strengthen the tube at some increase in the tube's weight.

Both deflection methods have advantages. Magnetic deflection is the logical choice for displays using intensity modulation and large screen tubes. For applications involving high-speed deflection, as in fast-sweep laboratory oscilloscopes, electrostatic deflection is superior.

DISPLAY SCREEN

Ultimately the electron beam must be converted to light. This occurs when the beam strikes the phosphor coating inside the glass CRT face plate. The light emitting properties of the phosphor coating can be extensively varied depending on the composition of the phosphor.

HUMAN EYE

SPECTRAL RESPONSE

The characteristics of the human eye together with the system's requirements are the considerations for specifying phosphor performance. The physiology and neurology of the eye are well described in the medical literature. There are, however, two characteristics of the eye that are prime considerations in choosing phosphors. These are the spectral response of the retina and its image retentivity.

A normal eye, when adapted to daylight viewing conditions (photopic vision), has its highest response to light in the green part of the spectrum at a wavelength of 555 nanometers. When adapted to dark viewing conditions (scotopic vision), the color sensitivity of the normal eye shifts toward the blue part of the spectrum with a peak response at 510 nanometers. The complete spectral response for both dark and light adapted vision is shown in Figure 3.

IMAGE RETENTION

An image focused on the retina will appear to remain for about 1/20 second after the light causing the image has ceased. This retinal retentivity makes possible the phenomenon of apparent continuous motion in "moving pictures" and television.

Consideration of the eye's color sensitivity and image retentivity provides significant design criteria for choosing phosphors for a given display application.

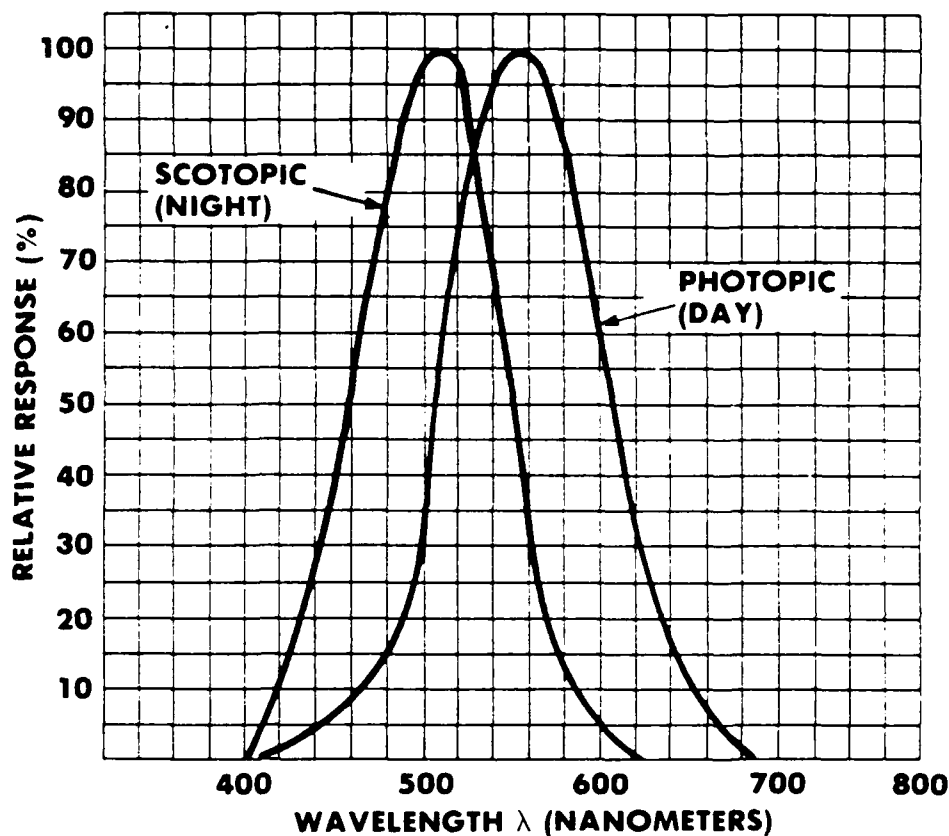


Figure 3. Relative Response Average Normal Eye³

CRT PHOSPHORS

Important properties of phosphor screens are light emitting efficiency, persistence of emission (decay time), and color.

PHOSPHOR EFFICIENCY

The ability to project a high-energy, sharply-focused electron beam on the phosphor screen is limited by the physics of electron behavior and the inevitable compromises in the design of the electron gun and deflection mechanism. Spot size, for example, increases with beam intensity. Therefore increasing the energy of the electron beam to increase light output is accompanied by spot growth and diminished resolution. Resolution then is one limit on beam intensity. Because the electron beam intensity can not be increased indefinitely, phosphor efficiency becomes a matter of keen interest to display designers. Phosphors with greater light producing efficiency are used to compensate deficiencies in electron beam energy and produce a brighter display.

PHOSPHOR COLOR

For systems in which a given picture element has a low refresh frequency, light output will be correspondingly limited. In this circumstance the designer would choose a high efficiency phosphor whose emission is in the region of the spectrum where the eye is most sensitive. If photography of the display is important, the spectral properties of the phosphor should be matched to the light sensitivity of the film. Light emitting spectra of several well know phosphors are shown in the curves of Figure 4.

PHOSPHOR PERSISTENCE

The light output of an electron-excited phosphor continues after the excitation is removed but diminishes over time until extinction. This property of light decay is called persistence. Persistence is measured from excitation cut-off to the time when light output reaches 10% of its peak value. Phosphor persistence ranges from 0.1 microsecond to 100 seconds. For displays having a repetition frequency (frame rate) faster than the eye's ability to discern flicker, phosphor persistence can be anything from 0 to 50 milliseconds. Applications where flicker is perceptible (frame rates less than 20 per second) require a persistence between 60-100 milliseconds to smooth out the flicker. For unprocessed radar displays where the signal is refreshed only 2 or 3 times per minute, the most persistent phosphors are required. Figure 5 shows persistence curves of some commonly used phosphors.

Some screens, designed for long persistence, are composed of cascaded phosphors. The P7 phosphor, which was developed for Plan Position Indicator (PPI)* radar displays, has a phosphorescent layer laid down on the glass screen. A second layer phosphor covers the back of this layer and is directly excited by the electron beam. The light flash caused by the impact of the electron beam on the back layer excites the front phosphor layer which then emits a longer lasting light radiation at lower intensity and longer wavelength. Light emission caused by electron impact is called fluorescence while light-stimulated secondary emission is phosphorescence. Figure 6(a) shows the emission color and persistence properties of standard phosphors. The range of decay time for various phosphors is shown in Figure 6(b).

ELECTRON BEAM MOTION

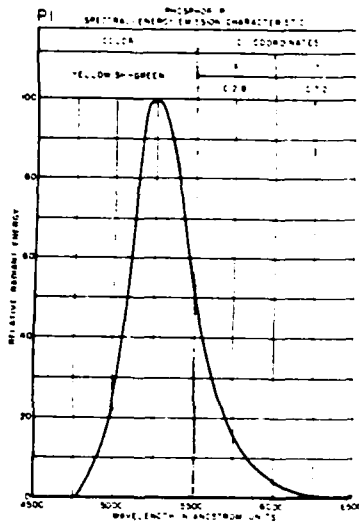
The ability to generate light by directing a focused beam of electrons on a phosphor screen has made electronic display of symbols and moving graphics a reality. By causing the electron beam to move over the phosphor display screen, the CRT can create images in two ways--random writing and systematic scanning.

RANDOM WRITING

In the "random write" method the electron beam is moved as one would move a pencil to print or draw an image. This method, illustrated in Figure 7, involves moving an electron beam to a desired position, turning it on, and drawing a symbol. When the line or symbol is completed, the beam is turned off so that it can be moved directly to another location where it can be turned on again to write or draw the next symbol.

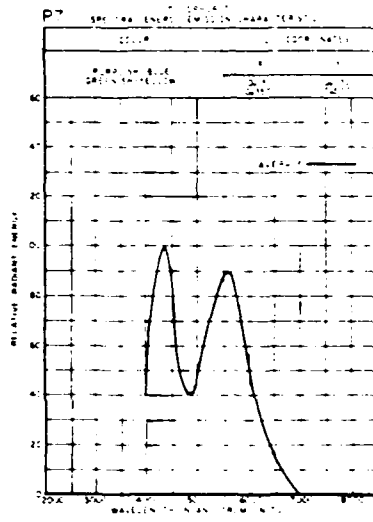
* In a PPI radar display the radar picture is developed by a rotating radial sweep.

**P1 - PHOSPHOR
(OSCILLOSCOPES)**



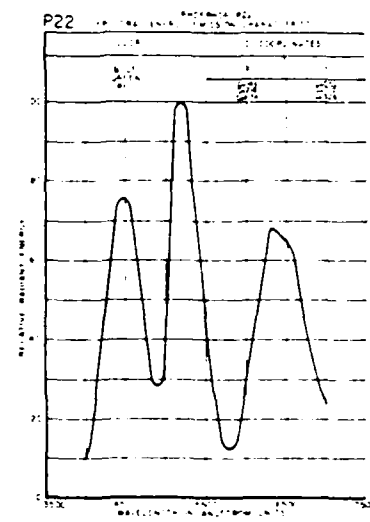
(a)

P7 - PHOSPHOR (RADAR)



(b)

P22 - PHOSPHOR (COLOR TV)

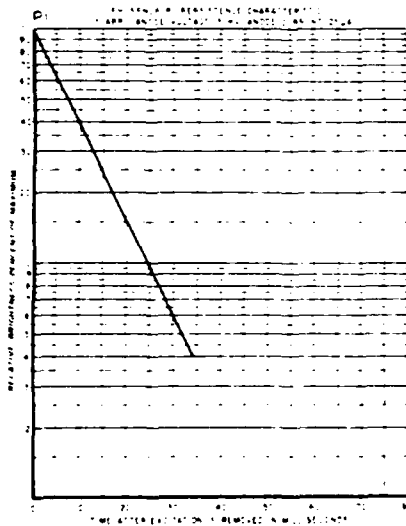


P22 STR-COLOR USING 3 DISTINCT PHOSPHORS.
BLUE-SIM TO ALL SULFIDE P4, GREEN-P, RED-P27

(c)

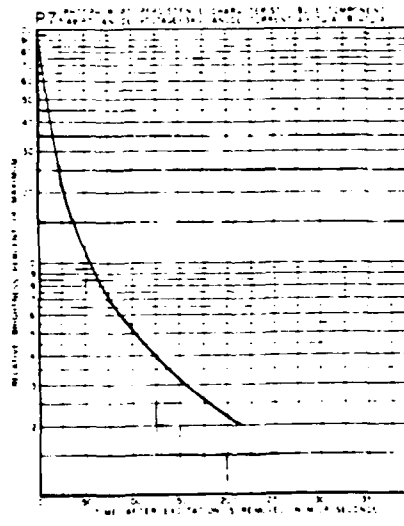
Figure 4. CRT Phosphor Spectra³

P1 - PERSISTENCE



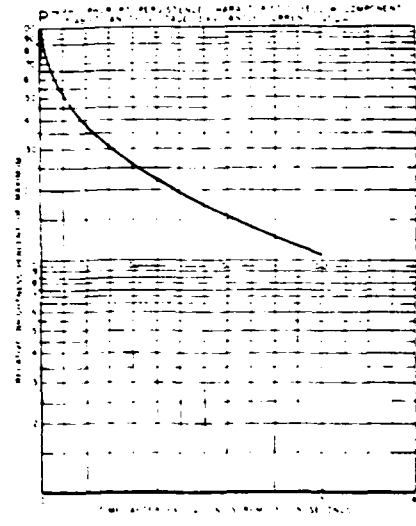
(a)

P7 - PERSISTENCE (BLUE)



(b)

P7 - PERSISTENCE (YELLOW)



(c)

Figure 5. CRT Phosphor Persistence³

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E I A PHOSPHOR	EMISSION COLOR		PERSISTENCE		APPLICATION
	FLUORESCENCE	PHOSPHORESCENCE	10%	1%	
P-1	Yellowish green	Yellowish green	24 ms	48 ms	Used in cathode ray oscilloscopes and radar
P-2	Yellowish green	Yellowish green	~ 75 μ s		Used in cathode ray oscilloscopes
P-3	Yellowish orange	Yellowish orange			
P-4	White	White	60 μ s	470 μ s	Used in monochrome television picture tubes
P-5	Blue	Blue	26 μ s	12 μ s	Photographic recording
P-6	White - Obscure	White			Obscure - Originally used in television picture tubes
P-7	White	Yellowish green	0.3 s	3 s	Used for radar
P-8	Obscure	Reddish orange			
P-9	Obscure				
P-10					Quickly decayed light is used for a situation. Persistence from 100 to 1000 μ s
P-11	Blue	Blue	50 μ s		Photographic recording
P-12	Orange	Orange	1.2 s	0.42 s	Used for radar
P-13	Reddish orange	Reddish orange			
P-14	Reddish orange	Yellowish orange	5 ms	170 ms	Used for color displays where persistence is 2 to 4 seconds
P-15	Green	Green	20 μ s		Television picture tube phosphors
P-16	Bluish green	Bluish green	10 μ s		Television picture tube phosphors
P-17	Yellowish orange to white	Yellow	0.4 s	10 s	Used for color displays
P-18	White	White	13 ms	37 ms	Used for color displays
P-19	Orange	Orange	0.22 s	0.22 s	Photographic recording
P-20	Yellow green	Yellow green	0.35 ms	1 ms	Photographic recording
P-21	Reddish orange	Reddish orange			
P-22	Two color phosphor screen				Used for color displays
P-23	White	White			Used for color displays
P-24	Green	Green	1.6 μ s		Used for color displays
P-25	Orange	Orange	40 ms	170 ms	Used for color displays where persistence is 2 to 4 seconds
P-26	Orange	Orange	12 s	19 s	Used for color displays
P-27	Reddish orange	Reddish orange	27 ms	15 ms	Color Television Monitor Service
P-28	Yellow green	Yellow green	0.6 s	6 s	Used for color displays
P-29	Two color phosphor screen				Used for color displays
P-30	Registration required without				
P-31	Green	Green	36 μ s	250 μ s	Used in oscilloscope tubes
P-32	Purplish blue	Yellowish green	0.7 s	6 s	Used for radar displays
P-33	Orange	Orange	2.2 s	15 s	Used for radar displays
P-34	Bluish green	Yellow green	100 s		Used for oscilloscope, radar, and visual information storage
P-35	Green	Green	0.8	5 ms	Used for photographic recording on orthochromatic film and visual observation
P-36	Yellow Green	Yellow green	250 ms	700 ms	Used for Flying Spot Scanners
P-37	Blue	Blue	150 ms	400 ms	Used for Flying Spot Scanner and photographic recording
P-38	Orange		1 s		Low Frame Rate Displays
P-39	Yellowish green		150 ms		Medium Frame Rate Displays and Radar
P-40	White		150 μ s	0.5 s	Reduced Flicker Console Displays

Figure 6 (a). Properties of Standard Phosphors³

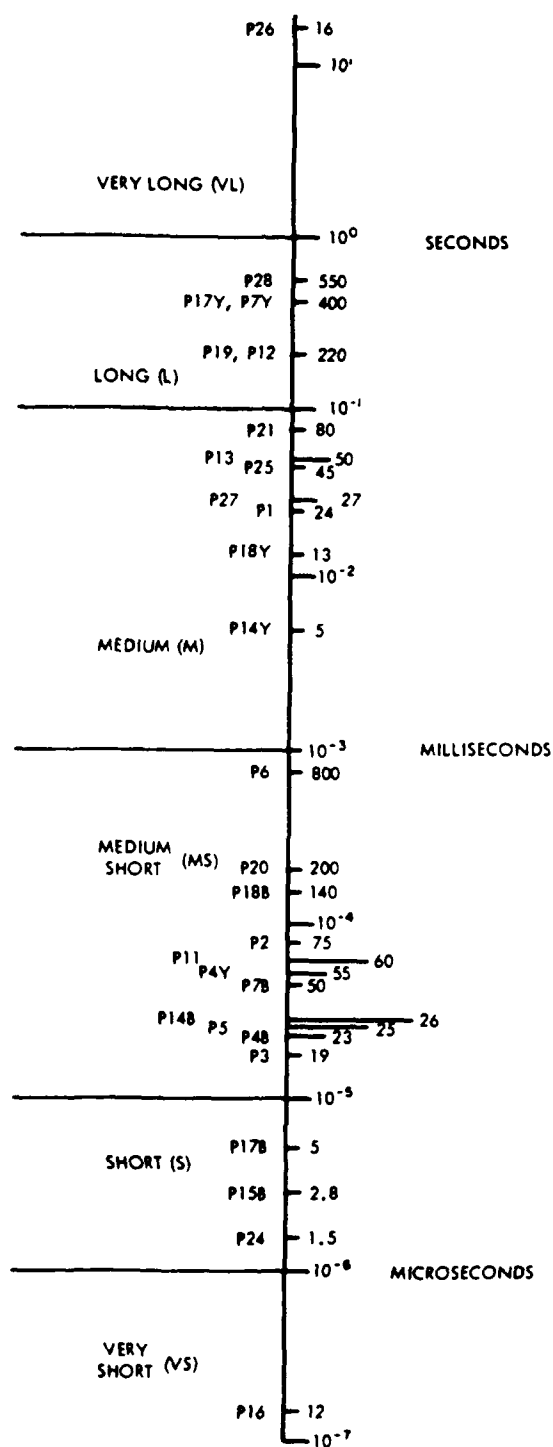


Figure 6(b). Decay Time of Various Phosphors²

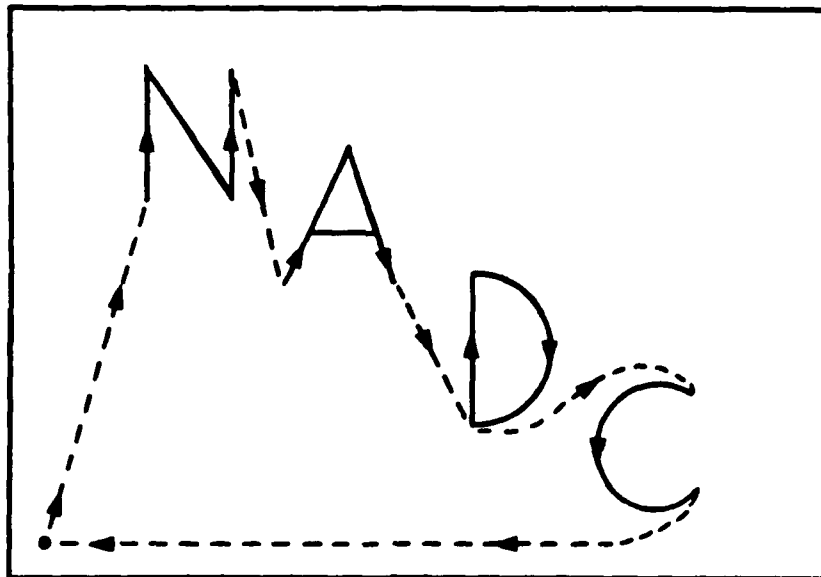


Figure 7. Random-Write Scanning Mode. Beam is at rest at lower left and follows the arrows to print the image. The beam is returned to origin after completing last character. The dashed lines indicate the beam is blanked but is turned on to draw the solid lines.

In the other mode of image generation the electron beam is caused to systematically traverse the whole display surface in a series of orderly, repetitive movements as opposed to random positioning. The image is created by brightening the beam when it passes over the locations which correspond to the bright elements in the image to be drawn. Usually the pattern of scanning is devised to fit the mechanism of a particular sensor system or image transmission system whose information is being displayed.

RADIAL SCANNING

Radial scanning was a natural method of presenting radar information. The quiescent position of the beam is at the center of a circular screen. The beam sweeps from the center to the periphery with uniform velocity producing a line whose deflection distance on the CRT screen is a linear function of time. This is called a linear sweep.

This center-to-edge sweep is repeated at frequencies of several hundred times per second and higher so that the quiescent beam spot at the center of the screen is converted into a radial line. The sweep brightness is intensified at points along the radial line corresponding to the range of various radar targets. Radar operators refer to this line as "range" because the distance from its origin at the center to a target indication represents the distance from the radar antenna to the actual target.

While the display sweeps out range lines the radar antenna continuously rotates so that it illuminates targets in different directions. An electro-mechanical linkage between the antenna and the deflection yoke causes the radial sweep on the CRT to rotate in synchronism with the antenna. The combination of

radial sweep and sweep rotation paints a full 360 degree picture of radar targets within the range of the radar set. This sweep mode enables the display to present the azimuth of targets as well as range. By combining the circular motion of the antenna with the radial sweep, the entire surface of the circular screen is covered forming a plan view of the volume of space above the radar antenna or of the earth surface below, depending on the location and orientation of the radar antenna. Targets existing in 3 dimensional space are displayed in two dimensional plan view: thus the term "PPI" plan position indicator has been used to describe this display.

RASTER SCANNING

By far, the most widely used method of systematic scanning is the raster scan. A raster is made by starting the beam at the top left corner of the display rectangle and moving it rapidly across the screen to the right creating a horizontal line. The beam is then blanked (turned off) and returned to the left side of the screen directly below and adjacent to the first line. The beam is then unblanked (turned on) to make a second excursion across the screen. This process is repeated until the whole screen area has been covered. Then the beam is blanked again and returned to the original starting spot to begin the next frame. This is the most simple type of rectilinear scan and is called progressive or non-interlaced scan. Figure 8 illustrates the pattern of progressive scanning.

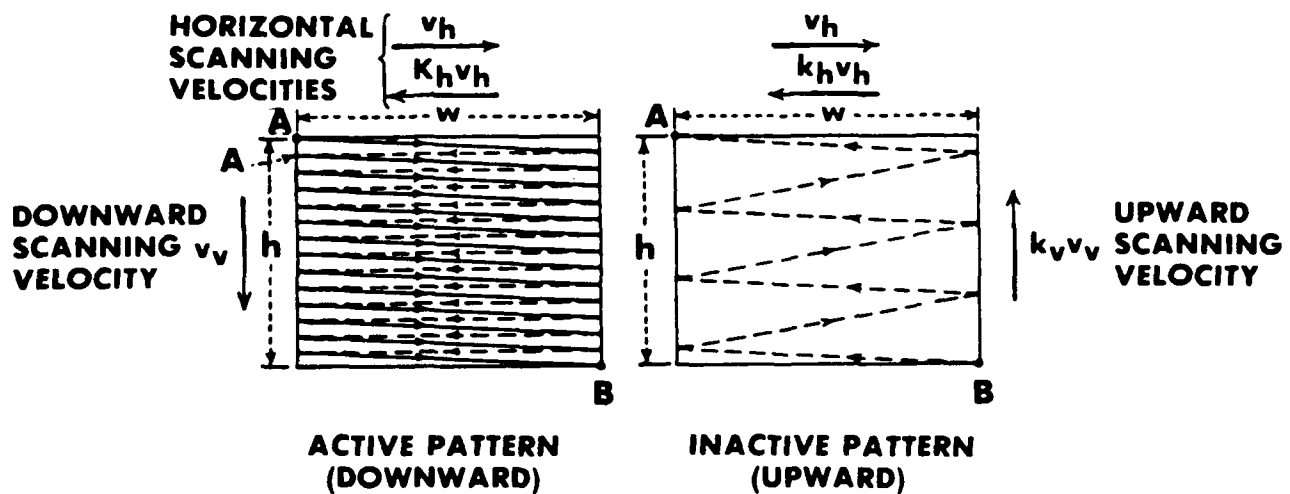


Figure 8. Pattern of Progressive Scan⁵. Left, the active (downward) scanning interval; right, the inactive (upward) period. The arrows indicate the direction of motion of the scanning spot.

INTERLACED RASTER SCAN

Television broadcasting in the United States uses a variation of progressive scanning called interlaced scan. The first line of interlaced scanning is located identically with the first line of progressive scanning. The next line and succeeding lines are spaced one line width from the previous line. On the first complete vertical pattern or "field", the display area is traversed using only half the lines used in the

progressive raster. On completion of the field the spot is blanked and returned to top center of the frame contiguous with the top line. The beam is then unblanked and begins the horizontal sweep of the second field (interlaced field) filling in the horizontal spaces left by the previous field. Completion of the second field completes one frame of the interlaced raster as shown in Figure 9. The eye sees the same information in one frame of interlaced scan as presented in a frame of progressive scan, but at twice the frequency because there are two fields for each frame in the interlaced raster. By doubling the frequency at which information is presented the viewer's perception of flicker is diminished.

The basis for U.S. television broadcast standards is the picture repetition rate (frame rate) of 30 per second. Because there are two fields per frame, the field rate is 60 per second. A frame contains 525 lines or 262 1/2 lines per field. To produce 525 lines 30 times each second requires a line rate (horizontal frequency) of 15.75 kilohertz. The ratio of picture width to picture height is set at 4:3.

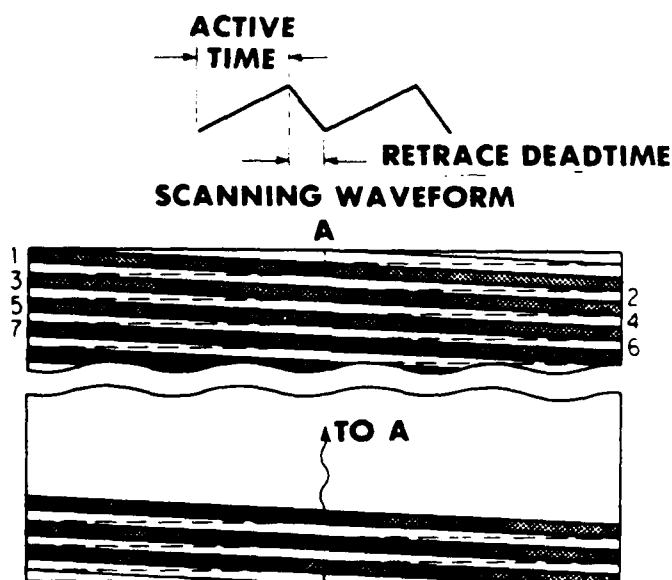


Figure 9. Interlaced Scan Pattern⁶

INTENSITY MODULATION OF RASTER

If the intensity of an electron beam is adjusted to produce a just visible trace, either progressive or interlaced scanning will generate an illuminated rectangle with a barely discernible line structure. The illuminated rectangle is called a raster. Of course, the light output from the CRT screen varies proportionately with the intensity of the electron beam. If the intensity of the beam is modulated in accordance with the luminance of a given picture or scene, such a picture will be reproduced by the light variations of the raster on the viewing screen.

COLOR CATHODE RAY TUBES

SHADOW MASK

A variety of schemes have been devised to obtain color images on a CRT. Some tubes are limited in the range of color produced; but if the object is to faithfully reproduce a scene in color, the tube must be able to generate the full range of colors in the visible spectrum. This can be done conveniently if the tube can produce the three primary colors red (R), green (G), and blue (B). By mixing combinations and intensities of the three primary colors, most other colors in the visible spectrum can be produced.

The schemes for generating full color either use three electron guns, each used to energize one of the primary color phosphors, or one electron gun that excites all three phosphors. In the one-gun tube, as the beam scans, it is gated "on" only when positioned on the desired color. Unlike the three gun tube a single-gun tube can illuminate only one phosphor at a time.

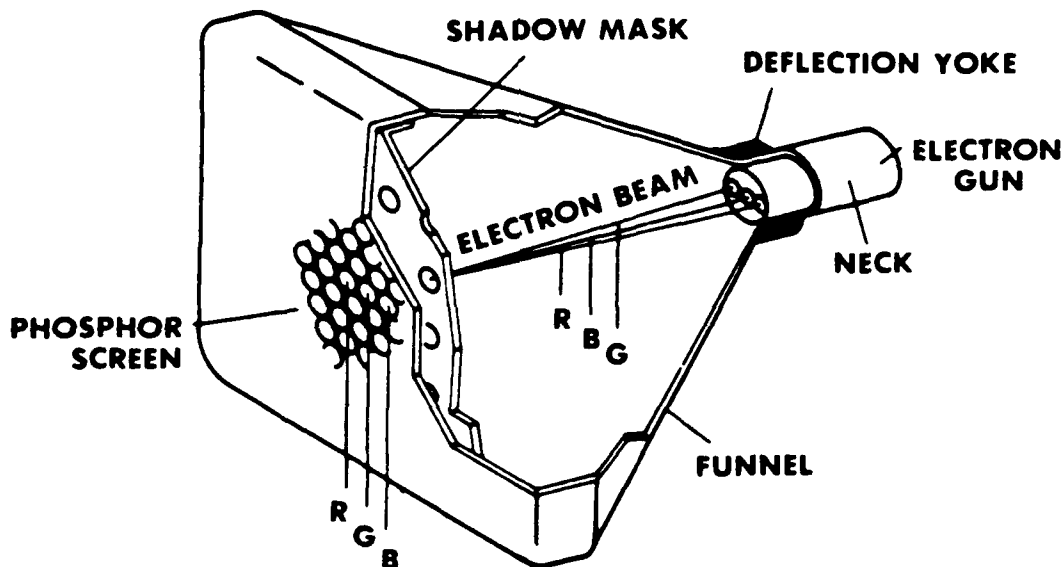


Figure 10. Shadow Mask Color CRT⁷

The shadow mask color CRT is, by far, the tube of choice due to its widespread use in commercial television. Figure 10 shows its essential construction. The tube uses three electron guns in either a triangular configuration (delta gun) or an "in-line" gun arrangement. In either case three electron beams are projected onto a viewing screen through a tiny aperture in the shadow mask. The axis of each beam intersects the hole at slightly different angles, causing the beams to strike the phosphor close together but in distinctly different places. The screen is composed of tiny individual dots of red, green, and blue phosphor. They are grouped together in triads, arranged such that each shadow mask hole permits the three electron beams to impinge on corresponding red, green, or blue phosphor dots--the same beam always illuminating the same dot. The dot size and their spacing within the triad is sufficiently small so that the eye perceives them as being a blend of color in one location. By addition of different intensities of the three dots most colors in the visual spectrum can be generated and a particular color will appear to come from a single position on the display screen.

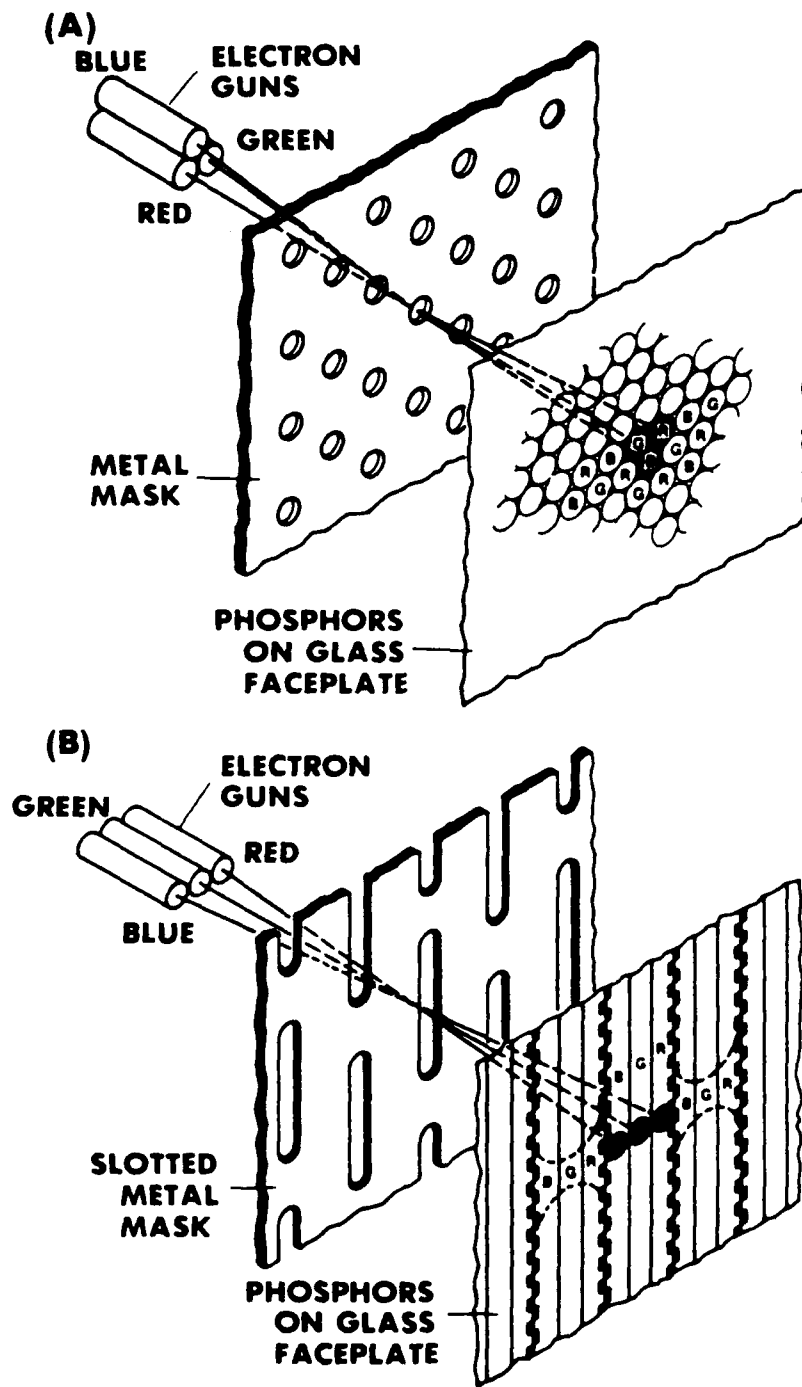


Figure 11. Shadow mask CRTs⁷. (A) Delta gun arrangement with dot-patterned phosphor, (B) In-line gun arrangement with stripe-patterned phosphor.

To create a horizontal sweep line the three beams are deflected equally and simultaneously in a horizontal direction. The beams will then encounter the next small hole in the shadow mask to illuminate the next triad of phosphor dots. As the beam continues its horizontal path, a succession of triads are scanned, producing a line whose color corresponds to the relative intensities of the three electron beams during the scanning. The electron beam intensities are controlled by the amplitudes of three separate video signals corresponding to the red, green, and blue components of the color being reproduced. Each video signal is applied between the grid and cathode electrodes of each electron gun permitting control or modulation of the intensity of each electron beam.

The purpose of the shadow mask is to limit the diameter of the electron beam so that it illuminates only one color of the phosphor triad and no other. In accomplishing this purpose, a portion of the electron beam is blocked from reaching the screen. In effect the screen is "shadowed". This process wastes a substantial portion of the beam energy resulting in a limitation of tube brightness.

Figure 11a. illustrates a delta gun tube with a shadow mask and a screen composed of color triads. Another configuration of a shadow mask tube has the electron guns positioned in line rather than in a triangle. The viewing screen for the "in-line" version has the R, G, B phosphor laid down in vertical stripes. The shadow mask apertures are in the form of vertical slots (see Figure 11b)

PENETRON

The penetron color tube was developed from research done at the Naval Research Laboratory and General Electric Co. As the name implies, the penetron operates on the principle of electron penetration into solids due to its velocity. In this case the solids are color phosphors layered on the CRT screen. In theory the penetron could have three phosphor layers to produce the full spectrum of visible colors; however, two of the phosphors would have to be transparent which at the current state-of-the-art limits color fidelity and brightness. Color selection is determined by beam penetration to the desired phosphor layer. Penetration depth depends on beam energy which is controlled by tube acceleration voltage. Accelerating voltages on the order of 15 kilovolts are typical with about a 5 kilovolt differential to select different colors. To switch voltages of this magnitude is a relatively slow process which limits a single gun tube to color switching at frame rates. The problems of color dilution and high-voltage switching speed have prevented the three primary color penetron phosphor tube from being practically achievable.

Tubes with two phosphor layers, usually red and green, have been successfully developed. Although the color switching is too slow for TV, the tube performs well in stroke writing applications where its resolution and brightness are superior to the shadow mask tube.

Problems which currently limit the performance of the penetron are: 1-lack of color purity due to filtering effects of intervening phosphors, 2-spurious excitation of the near phosphor when exciting the far phosphor, 3-degraded luminous efficiency due to compromises in beam energy necessitated by color switching, and 4-registration problems due to change in deflection sensitivity when the beam accelerating voltage is switched.

BEAM-INDEX COLOR TUBE^{11,12}

Beam indexing, as a technique for producing color, is unlike the shadow mask or phosphor penetration methods. The shadow mask tube excites three primary colors at the same time while the penetron excites color phosphors serially by depth penetration. Penetron colors are switched slowly at frame rate. The beam-index tube also excites colors serially but does it by scanning them at horizontal line rate.

NADC-88092-60

The beam-index color tube uses one electron gun, whose beam scans horizontally across a screen composed of thin vertical stripes of red, green, and blue phosphor. A wire or thin stripe is placed between each group of color stripes. When the scanning beam strikes the wire, it radiates a secondary emission of x-rays or ultra-violet light, depending on the tube design. This emission is detected by a built-in sensor and converted to a voltage or "index" pulse that identifies the position of the electron beam on the tube face relative to the next three color stripes in the scan path.

To reproduce a color of a given picture element on a beam-index tube, the electron beam must be intensity modulated for each of the three primary color components (red, green, & blue) of that picture element. Since the beam scans across the R, G, B phosphor stripes sequentially, its intensity must be changed for each stripe so that the three intensities represent the R, G, B color components of the picture element being reproduced. The eye sees these three illuminations, which are separated both in time and space, as one illumination in one place. The eye also sees the three individual colors as one color which is an additive mixture of the three. Thus any spot or picture element (pixel) can be displayed in any color of the visible spectrum.

Accurate color registration and color fidelity require the beam to be turned on only when it is located on one of the color stripes and no other. Switching with such precision is accomplished by using the index pulses as a repetitive time reference to determine when the electron beam, modulated by the appropriate R, G, B video signal, will be switched on and off. The beam must be turned off as it transits from one color stripe to the next. The index pulse also serves as a reference for synchronizing the switching between the red, green, and blue video signals. To achieve beam switching of sufficient accuracy for faithful color reproduction requires the beam to scan the screen at an unvarying rate; or in other terminology, the CRT must have a deflection sweep of exceptional linearity.

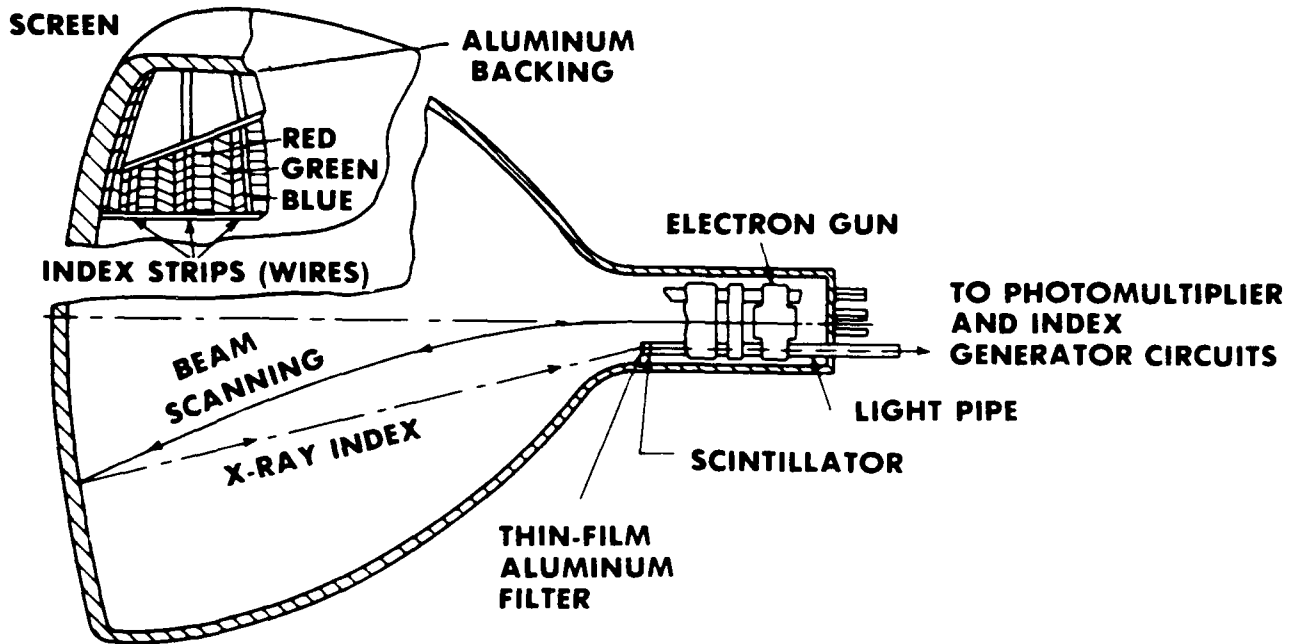
In U.S. commercial television there would be about 512 triads (each triad is one pixel) in a horizontal line and about 470 active horizontal lines. The CRT electron beam must be multiplexed 3 times for every pixel. At this rate the beam will excite a color stripe for only 35 nanoseconds (.035 microseconds) and the video driver and electron beam must respond from full "off" to full "on" in 10 nanoseconds or less, requiring a video channel bandwidth of 100 MHz.

Due to the location and dependence on the index stripe, the beam-index tube cannot operate in random write mode and is limited to raster type scanning. However, for raster displays the beam-index concept has great promise. The tube construction is almost as simple as that of a monochrome CRT making for low cost. The tube has a high resistance to shock and vibration and has no design features that limit size. Beam-index tubes can use magnetic focusing and should be capable of high resolution. Currently the tube is still in developmental stage. Additional engineering is needed to realize what appears to be the high-potential of the beam-index color tube concept. Figure 12 is a schematic drawing of the construction of the beam-index color tube.

OTHER COLOR TUBES

Various schemes and methods have been devised to produce color imagery on cathode ray tubes. Some are limited to special applications and others have not yet emerged from the laboratory to the market place. Some examples are the Lawrence Chromatron, the Greer 2-color thin tube, face plate geometry and the Mullard banana color tube.

There still remain many technical problems in the production of a satisfactory color display. The best display available today represents an artful compromise among many contending and often opposing design factors. No single color CRT design has emerged as ideal for all display applications. For the most part CRT designs tend to be special purpose rather than general purpose designs.

Figure 12. Schematic of Beam-Index Color Tube⁶

ESSENTIAL PERFORMANCE CHARACTERISTICS OF CRTs

BRIGHTNESS

The first subjective sensation produced by a light source or lighted area is a quality called brightness. Brightness is the response of the eye, specifically the retina, to the intensity of light emitted by a source or reflected from a surface. When brightness is measured as a physical quantity, it is called luminance. Brightness is measured in foot-candles^{*} for a light source and foot-lamberts[†] for diffused light from a reflecting surface. In responding to the varying illumination levels in the natural and man-made environment the eye can accommodate a range of illumination between 10^{-5} and 10^5 foot-candles or a dynamic range of 10 billion to one. Typical environmental luminance values are given in the following table:

* A foot-candle is the intensity of illumination on a surface that is everywhere one foot from a uniform point source of light of one standard candle power.

† A foot-lambert is the luminance of perfect diffusing or reflecting surface which is illuminated by one foot-candle (or one lumen).

Table 1. Typical luminances (In Footlamberts)*

Surface of the sun.....	4.8×10^8
Surface of a 60-W frosted incandescent bulb ("hot spot").....	36,000
Brightest white cumulus cloud.....	12,000
Surface of a 60-W "white" incandescent bulb.....	9,000
White paper in direct sunlight—high sun.....	9,000
Surface of a 15-W fluorescent tube.....	3,000
Clear sky.....	2,000
Surface of moon, bright area.....	2,000
White paper on office desk.....	25
Pulsed electroluminescent mosaic panel.....	20
Television raster.....	20
Light valve, 10 × 10 ft diffusing screen, 2-kW lamp.....	20
Theater screen open gate.....	16
White paper in full moonlight.....	10^{-2}

* H. R. Luxenberg, Photometric Units, *Information Display, J. Soc. Inform. Display*, May/June, 1965, with additions by R. H. Akin and J. M. Hood, Jr.

The eye is a sensor that responds to electromagnetic radiation between 400 to 700 nanometers wavelength. The standard observer curve Figure 3 shows the relative response of the average normal eye to light containing constant radiant energy in the wavelength band between 400 and 700 nanometers. It is the eye's response that defines the portion of the electromagnetic spectrum known as "light". If the light being viewed is not monochromatic, the eye will integrate the total energy curve. This results in the subjective sensation of brightness.

A photometer for measuring luminance (brightness)* must have a response to radiant energy corresponding to the eye response at each wavelength. Such an instrument is said to have a photopic response. This is accomplished in a modern objective electronic photometer by modifying the photomultiplier response with appropriate optical filters. Deviation of the photometer response from the standard observer curve is one of the pitfalls of accurate and repeatable photometry.

The brightness of a display is almost universally quoted or specified as though it were a definitive characteristic. More brightness, however, is not necessarily better. For example, under a controlled test¹⁸, when maximum illuminations available for reading were 10, 30, and 45 foot-candles, the observers selected 5, 12, and 16 foot-candles as optimum values.

The brightness of a display is important mainly because of its relation to contrast. In a situation where the display must operate in high ambient illumination which is not controllable by the operator,

* Current monochrome CRT displays have a brightness range of 50 to 10,000 foot-lamberts. Color CRTs range from 50 to 200 foot-lamberts.

NADC-88092-60

higher brightness may be required to provide acceptable contrast. Color response of the retina and the ability of the eye to perceive fine detail are dependent upon brightness.

Photopic vision, for example, requires brightness above 1.0 foot-lambert. At .01 foot-lamberts scotopic adaption takes place and the ability of the eye to sense hue and saturation disappears.

CONTRAST

The significant problem of obtaining display contrast adequate to reproduce a complex scene involves not only the technical performance of the display system but also the ability to see. Seeing is a complex physiological and psychological process in which contrast is a factor of high importance⁸.

Brightness and contrast are closely related to each other and to visual acuity². Contrast, according to the lexicon, means the difference between two items compared side-by-side. In display technology the items being compared are the brightness of the highlight and dim areas of the CRT image. Contrast can also refer to differences in color (color contrast), but most often refers to brightness. Brightness when measured as a physical quantity is called luminance.

Contrast is sometimes referred to as contrast ratio and is expressed by the ratio of the luminance measurements of two areas. Two definitions have been devised to quantify contrast. Contrast ratio is given by -

$$CR = \frac{L_2}{L_1} \quad (1)$$

in which L_2 and L_1 are luminance measurements and $L_2 > L_1$. In display application L_2 would be measured in the brightest image highlight and L_1 would be a background measurement in a dark, non-illuminated area of the display. Contrast ratio can be measured with or without ambient illumination. However, if the ambient illumination is to be included, both L_2 and L_1 must include the ambient illumination in their measurement. The two luminance values (L_2 , L_1) can be measured at widely separated parts of the display screen in order to establish the full brightness range. From this value the maximum number of gray shades can be determined.

Contrast is also defined as a percentage on a closed scale of 0 to 100 by taking the difference between two luminance measurements and dividing by the larger luminance. Equation (2) is the accepted formulation of percentage contrast ($C\%$) when the image is darker than the surrounding background.

$$C\% = \frac{L_2 - L_1}{L_2} \times 100 \quad (2)$$

L_2 is the luminance of a radiant display element under a given ambient illumination and L_1 is the luminance of an adjacent non-radiating element under the same ambient illumination. This contrast definition is used when ambient illumination is a significant portion of display brightness and for discussion of visual acuity.

To fully describe a tube's contrast performance at least two kinds of contrast measurement are required. One is an overall measurement called contrast range and the other is detail contrast. Contrast range is measured with half the CRT screen illuminated at full brightness and the other half completely dark. The luminance measurements are made in the center of each area and the test is conducted without ambient illumination. The contrast ratio, thus obtained, can be used to compute the maximum gray shades the tube can produce.

NADC-88092-60

Detail contrast represents the CRT's ability to reproduce brightness variations in small details of the picture. A typical test pattern for measuring detail contrast is a raster of maximum brightness with a dark area (beam cut off) 0.5" by 0.5" in the center of the raster. Luminance measurements are made in the center of the bright area (L_2) and the center of the dark area (L_1). When this measurement is made in the absence of ambient illumination it is a measure of the contrast which is limited by halation, a phenomenon common to all CRT screens.

Factors Detrimental to Contrast

We have defined contrast and described two methods of contrast measurement. It is appropriate now to consider some of the factors detrimental to contrast.²¹ In modern cathode ray tubes contrast is degraded by spurious excitation due to screen curvature, light reflections from the internal bulb wall, halation, and ambient illumination.⁸

Screen Curvature

Figure 13 shows a schematic diagram of a CRT with the electron beam impinging on point A. The phosphor at this spot is brightly lit and light from point A scatters in all directions. Some of the light flux output from point A is radiated through the bulb face to the observer represented by arrows A-O. Other rays from point A radiate along the path indicated by arrows A-C.

Because the phosphor is a perfect diffusing surface, light rays striking point B are scattered in all directions which include the path through the screen to the observer. If point B is intended to be a dark area of the scene, its contrast will be reduced by the spurious rays from point B caused by radiation from point A.

Internal Bulb-Wall Reflections

In Figure 14 the same CRT is shown with the same point A being excited by the electron beam and point B, a dark area of the image, receiving a portion of the light radiated from point A. Figure 14 also shows an example of the light paths inside the CRT bulb which contribute to the further degradation of contrast. Because point A radiates luminous flux in all directions, a ray A-R will strike the bulb wall where it will be reflected and scattered.

Ultimately it will reach point B on the screen via paths N and M. At point B it will be diffused by the phosphor thereby increasing the illumination of a dark area causing further reduction of image contrast.

Halation

Halation is an optical process that produces unwanted halos of dim fluorescence around small bright areas of a display image. The effect of halation makes dark parts of the image lighter which, of course, reduces desired contrast. In Figure 15 "O" is a small bright area caused by the electron beam exciting the phosphor. "O" will appear as a bright spot on the face of the CRT as shown in the top view of Figure 15. Light ray "O-1" will strike the glass-air interface (see cross section in Figure 15) perpendicularly and will exit the CRT face undeflected. Rays O-2 and O-3 strike the interface at oblique angles of incidence and are refracted away from the perpendicular towards the tube face. The larger the angle of incidence, the more the ray will bend away from the normal toward the glass face. When the angle of incidence of a ray reaches the critical angle O_c , the ray no longer refracts but reflects back through the face plate and strikes the phosphor layer where it is diffused again in all directions. This appears as a weakly illuminated area to the viewer; but because the rays are radiated in all directions from the original spot "O", the spurious light appears as a dim circle surrounding the spot. Any rays radiated from the halo that strike the interior glass face at the critical angle of incidence or greater angle

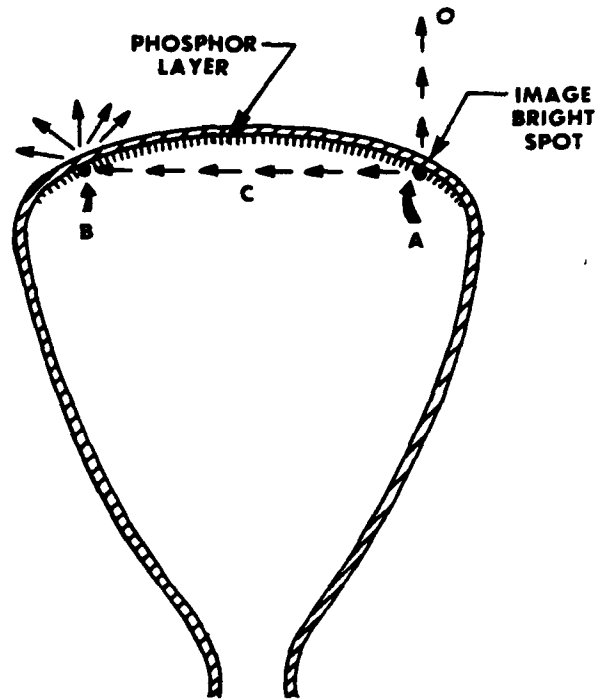


Figure 13. Longitudinal Cross Section of CRT Showing Effect of Screen Curvature on Contrast⁸

INTERNAL BULB-WALL REFLECTIONS

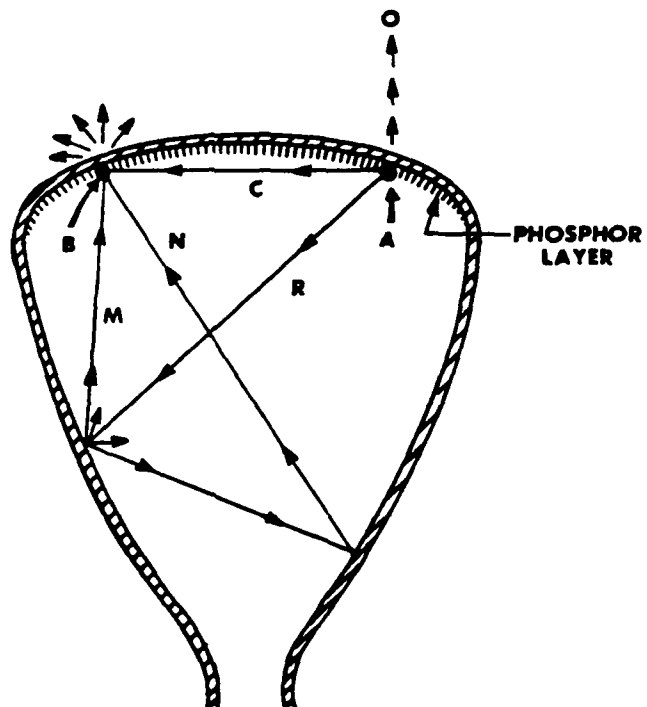


Figure 14. Effect of Internal Reflection on CRT Contrast⁸

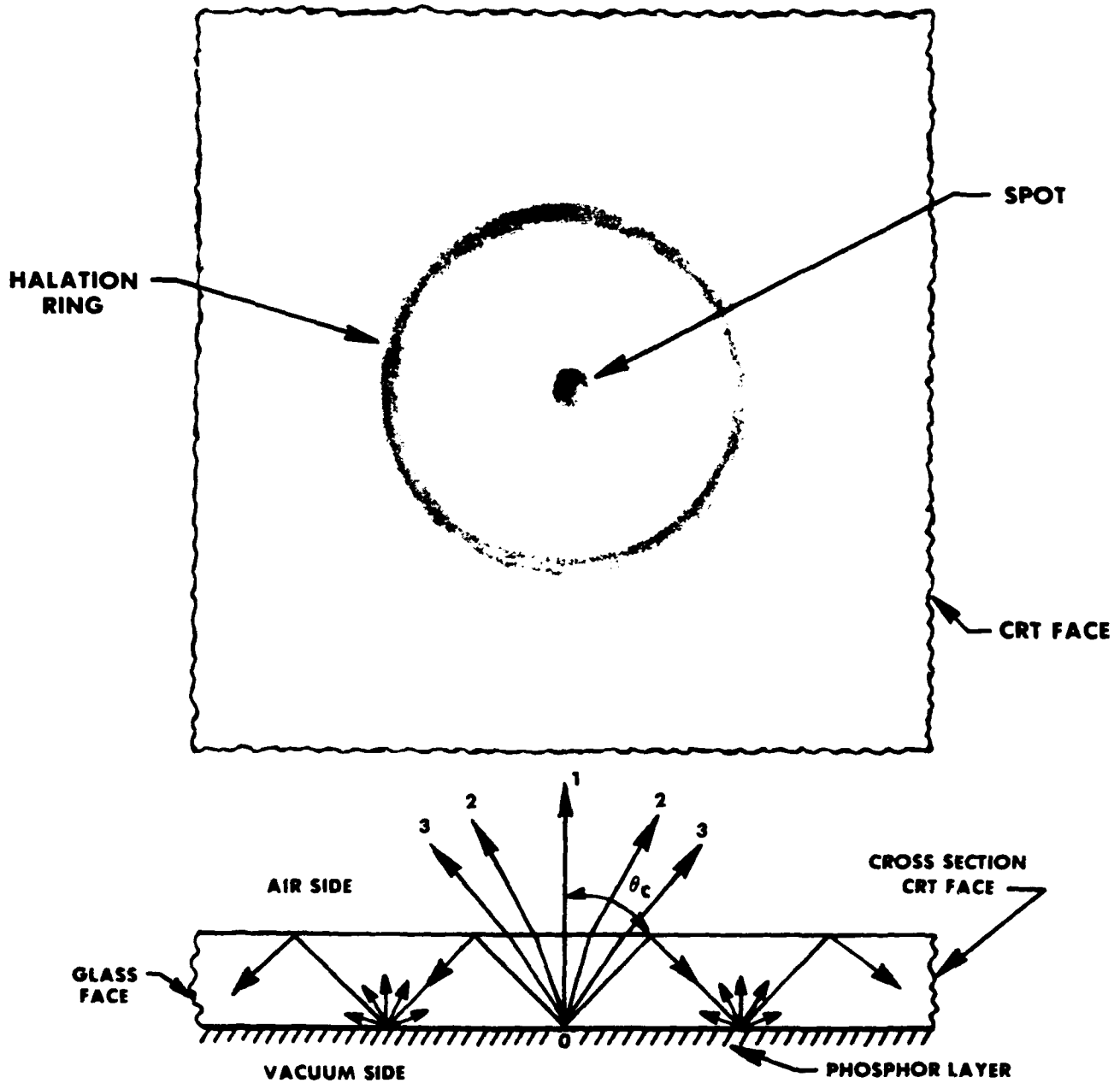


Figure 15. Cross Section and Face View of CRT Screen Showing How Total Internal Reflections Produce Halation⁸

NADC-88092-60

will likewise be reflected back to the phosphor causing another, much dimmer halo concentric with the first one⁸.

In a picture or complex pattern, apparent contrast depends on the brightness gradient between two adjacent areas or picture elements. This is the property of visual display we recognize as detail contrast. Because halation causes extraneous low-intensity illumination in an area of 2 to 3 square inches surrounding an image highlight, it severely limits detail contrast. The effect of halation reduces detail contrast of a CRT to a value of 10 to 15:1. The maximum large area or contrast range is typically 50:1. Optical filtering is one approach to increasing contrast. Neutral density filters with a transmission of 20% will increase detail contrast to 25:1 and range contrast to 100:1.⁸

Ambient Illumination

A factor that is usually not under the control of the designer, but one having a large effect on CRT contrast, is the intensity of the ambient illumination where the display is viewed. Some situations permit a degree of control over ambient light. Where this is not possible, the designer is forced to compete with environmental lighting by optimizing CRT design. To increase contrast in high ambient illumination he will utilize light control measures such as optical filters, filters with spectral characteristics matched to the phosphor spectrum, polarization techniques, and high brightness phosphors.

Conventional phosphors are near white in color and have a reflectivity of 50% to 80%. In a high ambient environment, the light reflected by white phosphors can obliterate the display image. For readability, image brightness must greatly exceed the brightness of ambient light reflected from the phosphor.⁵

Consider a conventional powdered phosphor screen. Figure 16 is a schematic diagram of the tube showing the details of the screen construction. Assume a 50% reflectance for the phosphor screen and 100 foot-candles of ambient illumination incident to the tube face, then the darkest area of the picture will have a brightness of 50 foot-lamberts. If the brightest highlight in the image is 100 foot-lamberts the display will have a maximum contrast ratio of

$$C_R = \frac{L_2}{L_1} = \frac{150}{50} = 3:1.$$

This restricted brightness range would produce no more than 3 shades of gray.⁹

This state of affairs can be improved by using a neutral density filter with 10% transmission bonded to the CRT face. Now the 100 foot-candle ambient illumination is reduced to 10 foot-candles at the phosphor. After light is reflected from the phosphor back to the observer, the filter again reduces its intensity to 0.5 foot-lamberts. The darkest part of the display now has a brightness of 0.5 foot-lamberts and the 100 foot-lambert highlight is also reduced by the filter to 10 foot-lamberts.⁹

The maximum contrast ratio is now

$$C_R = \frac{10+0.5}{0.5} = 21:1$$

Thus the gain in contrast is achieved at a cost of 90% of the maximum brightness. Under these conditions 9 shades of gray are attainable. It should be noted that the neutral density filter also has the beneficial effect of reducing halation.⁹

This discussion does not take into account reflections of ambient light from the front surface of the CRT face plate. Optical coatings can reduce these reflections to about 1%.

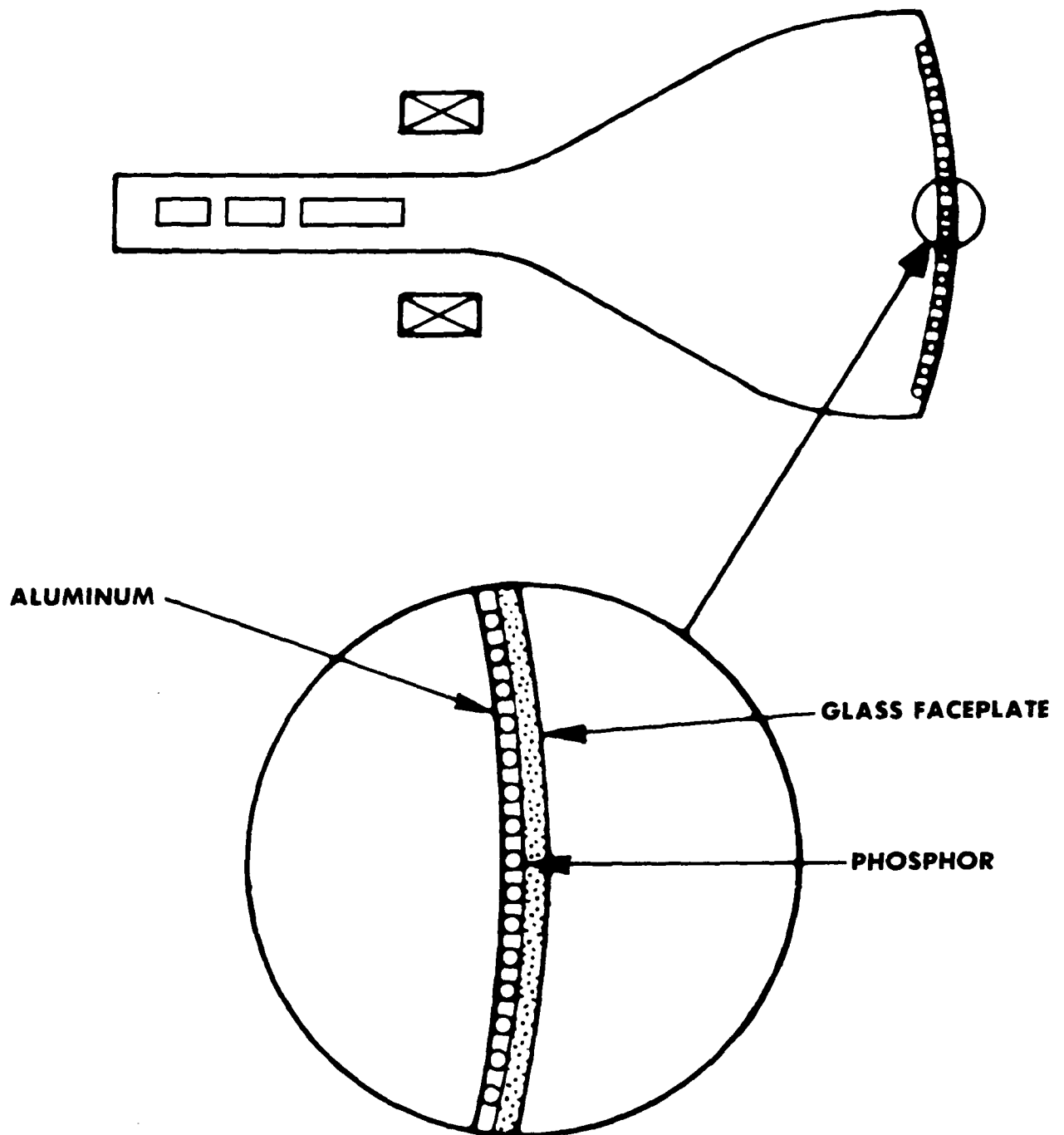


Figure 16. CRT with Conventional Powered Phosphor Screen⁹

NADC-88092-60

A technique also used in flat panel design is to replace the highly reflective white powder phosphor with a thin continuous evaporated or vapor-deposited layers of transparent phosphor. Because these films are transparent, they reflect less than 2% of incident light. A black layer is formed behind the transparent phosphor to prevent the viewer from seeing the inside of the CRT. This layer is opaque to light but easily penetrated by the electron beam (see Figure 17).⁹ This design has the pleasant effect of displaying luminescent imagery against a black, light-absorbing background. Now if the simple analysis using the conditions cited in the previous example is applied, there will be an incident external illumination on the CRT face of 100 foot-candles. The darkest area of the image will reflect 2 foot-lamberts while the highlight luminance will be 102 foot-lamberts. The contrast ratio is now

$$CR = \frac{100+2}{2} = 51:1$$

permitting 12 shades of gray; quite an improvement over the powder phosphor at 3:1 contrast with 3 shades of gray. The transparency and low reflectivity of this film phosphors results in a substantial reduction of halation as well as an increase in contrast in bright environments.⁹

In cases where the available CRT brightness range is insufficient to permit the required brightness contrast, color contrast can be used to compensate for deficiency in brightness contrast.

Contrast Ratios in Everyday Subject Matter

If displays are to represent pictures of places and events such as are portrayed on television, infra red systems, or radar, the degree of realism will depend strongly on the display's ability to reproduce the range of brightness (contrast range) that is proportional to the brightness range found in everyday subject matter. Outdoor scenes in bright sunlight (10,000 foot candles) can produce contrasts of 10,000:1 between sky and deep shadow.⁵ In heavy overcast contrast may diminish to 2:1.⁵ Typical values of interior illumination, on the other hand, are:²

Normal Desk Work	25-50 ft. candles
Normal Recreation	10-20 ft. candles
Large Objects at Good Contrast	5-10 ft. candles
Normal Moving About	2.5 ft. candles

Therefore interior illumination levels represent a range of contrasts up to 50:1. State-of-the-art television systems are limited by design to a contrast ratio of 100:1 but, in practice, do well to achieve 50:1.⁵ These limitations are mainly the result of two factors. In television cameras, photo-electric emission saturates at high light levels while at low light levels signal currents fall below the "noise" generated by random photo-electric emission and thermal noise in video amplifiers. Moreover the CRT display (picture tube) contributes its own restriction on dynamic range due to halation at low light levels and phosphor saturation at high light levels.

Fortunately for display designers the various restrictions on dynamic brightness are to a large extent offset by the logarithmic response of the human visual system to light intensity. Because the eye responds to the logarithm of brightness, a contrast range as low as 50:1 can portray a scene with convincing realism.⁵

A display need not replicate the absolute brightness in the object scene. For example, a scene having a brightness range of 50 to 500 foot-lamberts can be reproduced convincingly with a CRT brightness range of 3 to 30 foot-lamberts. The requirement for acceptable reproduction is that the

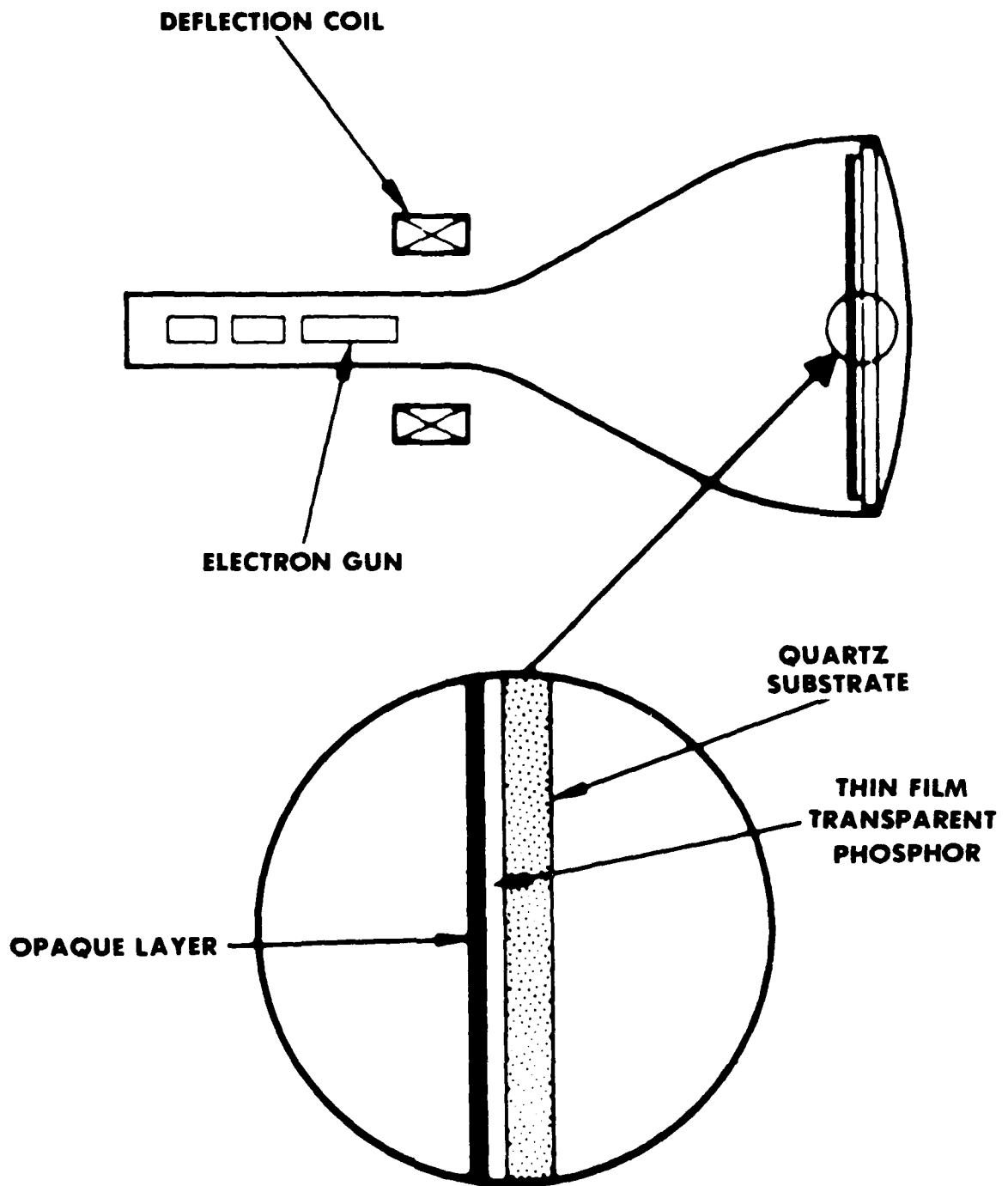


Figure 17. CRT with Transparent Phosphor and Opaque Backing⁹

NADC-88092-60

display brightness for a given picture element be proportional to the brightness of the corresponding element in the original scene. Notice in this example that both the object scene and reproduced image have a contrast ratio 10:1.

Contrast in CRT Displays

Acceptable brightness and contrast ratios are mainly a function of ambient illumination and the number of gray shades necessary to visually depict the information.⁵ Ambient light is one of a number of important factors which drive display design. When ambient illumination is known, detailed specifications such as luminance, resolution, and contrast can be derived.¹⁰

Sunlight falling on displays in combat aircraft can reach an illuminance of 10,000 foot-candles while illumination at ground interiors fall in the range of 1 to 70 foot-candles. Ambient light is the enemy of display contrast and where extraneous light can not be controlled, higher display brightness and optical filtering are required to maintain sufficient contrast. Assuming there is sufficient contrast and nominal ambient illumination, display brightness levels in the range of 20 to 70 foot-lamberts are workable.² In low ambient light, 1 to 10 foot-lamberts should be sufficient. For acuity, brightness should not be permitted to fall below 1.0 foot-lambert² to preserve the eye's light adaptation (cone vision). Dark adapted eyes rely mainly on rod vision which has a much lower resolving power.

Contrast ratios required to produce readability vary with subject matter. Acceptable contrast ratios are:^{21,6}

White symbols on black background	5:1
Line drawings or text on white background	25:1
Pictorial scenes	100:1

Summary

Visual information in a scene is conveyed by differences in brightness between adjacent picture elements.⁵ For this reason side-by-side picture elements must be capable of good contrast. This characteristic is measured by the factor previously defined as detail contrast. Halation is the most detrimental phenomenon limiting detail contrast. Reduction of halation can double or triple the shades of gray available for picture reproduction.⁸

It would be difficult to overestimate the importance of contrast as a factor affecting the performance of electronic displays. Contrast is related to brightness and ambient light, and is a factor affecting subjective sharpness of a displayed image.

GRAY SCALE

The most rudimentary electronic displays generate images by having the display elements either fully "on" (at maximum brightness) or fully "off" (dark). Usually the "on" or luminous elements form a geometrical shape against a dark background of non-illuminated elements. It is this shape or symbol that conveys the desired picture information to a viewer. Examples are line drawings and alpha numerics.

Since a picture is worth a thousand words, it was natural that displays were developed to present pictures capable of conveying details far more numerous and subtle than line images. This was accomplished by using all the display elements to "paint" a picture with each element having the

NADC-88092-60

capability of emitting intermediate shades of brightness rather than full "on" or fully "off". The objective of modulated light intensities is to represent the brightness values in the original scene by corresponding brightness values in the displayed image. The intermediate brightness levels between full "on" and full "off" are called shades of gray. Gray shades in a display serve the same purpose as those in a black and white photographic print.

The greater the brightness range, the more information the eye discerns. Information is transmitted in brightness variations which are identified as shades of gray. A gray shade is the minimum differential of brightness that the eye can detect.⁵

A television system must transmit high definition gray shades. To accomplish this the system must reproduce a large number of tone values which can only be displayed if the tube has a large over all contrast range.⁶ Studies have indicated that CRT luminance must change by a factor of $\sqrt{2}$ for the eye to perceive a change in brightness. Thus each successive gray shade must be an additional $\sqrt{2}$ times the luminance of the previous shade. Figure 18 tabulates the relationship between luminance, relative brightness, and shades of gray. Figure 19 shows the brightness range and gray scale content of typical indoor and outdoor scenes.

Current cathode ray tubes can produce 10 to 12 gray shades in a low ambient illumination. In a high ambient environment 6 to 8 shades can be attained using spectral filters. Display brightness and contrast requirements depend on the ambient illumination present and gray shades necessary to perform the task.⁵

RESOLUTION

Just as gray scale contributes to the realism of a displayed picture, resolution, which refers to the extent to which fine detail can be reproduced, is an important feature of image quality. In order for the observer to distinguish between adjacent objects or parts of the same object, it is necessary that the image contain distinguishable parts and the human visual system be capable of resolving those parts. The Society for Information Display defines resolution as "the ability to delineate picture detail; smallest discernible detail in a visual presentation."

Acuity, on the other hand, is a property of the eye which can be described as keenness of perception. Thus the precision with which pictorial information can be transferred in a visual system is limited, on one hand, by the resolution of the display and on the other, by the acuity of the eye. One can speak of the resolution of the eye but not the acuity of a display. When referring to the resolution of the eye, we are describing the anatomy of the retina and the corneal lens.

Eye Anatomy⁶

The retina is an extension of the optic nerve and covers most of the posterior eye chamber. The tissue of the optic nerve and the retina resembles that of the brain. Two photo sensitive cell types composing the retinal surface are called rods and cones based upon their appearance. They are perpendicular, to the retinal surface and form a closely packed mosaic of photo sensors. Except in the fovea the rod light receptors are mixed with cones and their density increases toward the periphery of the retina. The entire retina contains 110×10^6 to 130×10^6 rods but only 3×10^6 to 7×10^6 cones.⁶

In the part of the retina behind the eye lens and centered on the visual axis is a small depression about 0.4 to 0.5 millimeters in diameter called the fovea centralis or just fovea.⁶ This is the retinal area with a high density of cone light receptors. There are no rods in the fovea. The fovea is also distinctive because the neural layers of the retina are thinner and present less attenuation to light.

NUMBER OF GRAY SHADES	RELATIVE BRIGHTNESS	
1	$(\sqrt{2})^0$	1.0
2	$(\sqrt{2})^1$	1.4
3	$(\sqrt{2})^2$	2.0
4	$(\sqrt{2})^3$	2.8
5	$(\sqrt{2})^4$	4.0
6	$(\sqrt{2})^5$	5.6
7	$(\sqrt{2})^6$	8.0
8	$(\sqrt{2})^7$	11.2
9	$(\sqrt{2})^8$	16.0
10	$(\sqrt{2})^9$	22.4
11	$(\sqrt{2})^{10}$	32.0
12	$(\sqrt{2})^{11}$	45.0
13	$(\sqrt{2})^{12}$	64.0
14	$(\sqrt{2})^{13}$	89.5
15	$(\sqrt{2})^{14}$	128.0
16	$(\sqrt{2})^{15}$	179.0
17	$(\sqrt{2})^{16}$	256.0
18	$(\sqrt{2})^{17}$	358.0

Figure 18. Gray Shades, Relative Brightness, and Luminance Contrast⁹

SCENE	BRIGHTNESS RANGE	NUMBER OF GRAY SHADES
CLEAR SUNLIGHT AND SHADOW	100 PLUS	14 PLUS
NORMAL LANDSCAPE	30 TO 50	11 TO 12
INTERIOR WITH NORMAL ARTIFICIAL ILLUMINATION	20 TO 50	9 TO 12
MOVING-PICTURE SCREEN	50 TO 100	12 TO 14
GOOD PHOTOGRAPH	15 TO 40	9 TO 12
REQUIRED FOR GOOD TELEVISION HIGH QUALITY TELEVISION	15 TO 20 100	9 TO 10 14

Figure 19. Brightness Range and Gray Shades in Familiar Scenes⁹

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The fovea is the seat of the most sensitive vision due to the concentration of cones and diminished light attenuation by the thinner neural layers. Color and detail recognition is best when the image is focused on the fovea*. For images focused 1° off the visual axis (therefore off the fovea centralis) the resolving power drops by 30 to 40 percent.

There are at least five types of visual acuity. One of these is "minimum separable acuity." The structure of the fovea is such that two separate objects can be distinguished if their image on the retina has a spacing of at least one cone width. Individual visual elements considerably smaller than the diameter of one cone will be visible if their brightness is sufficient to stimulate a cone.

The focal length of the eye is about 15mm. If we assume a cone dimension to be one micro meter, this will correspond to a visual angle of 6.7×10^{-5} radians, 0.23 minutes of arc, or 3.8×10^{-3} degrees. Superficially it would appear that a target would have to subtend this angle to be observed. However a single high-contrast target subtending as little as 2.4 micro-radians (2.4×10^{-6} radians) or 0.5 seconds of arc can be detected.⁶ This will be explained further in the discussion of display resolution.

Visual Acuity²

The ability of the eye to see fine detail cannot be expressed using a single definition or method of measurement. The measurement of acuity varies according to the visual tasks.

Five types of measurement currently of interest in the display field are as follows:

Minimum visible acuity	}	Minimum detectable acuity
Minimum perceptible acuity		
Minimum separable acuity		
Vernier acuity		
Stereoscopic acuity		

Minimum detectable acuity refers to the minimum size an object must be to be seen at all. If such an object is seen, it will appear to have the size of the minimum resolvable spot size of the eye.[†] Nevertheless its actual size can be much smaller.

* This holds true for the photopically adapted eye.

† Minimum resolvable spot size is the area of one cone (1.0 to 3.0 micro meters in diameter, or 0.23 minutes of arc to 0.69 minutes of arc).

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Minimum detectable acuity is not only dependent on brightness and contrast but also depends on whether the object is a bright spot on a dark background (minimum visible acuity) or a dark spot on a bright background (minimum perceptible acuity). The reason for this difference is that bright objects tend to appear larger than they actually are. This occurs because once the eye's light receptor (cone or rod) is triggered, the object appears as large as the receptor.* On the other hand a small dark object will not be noticed because the background is now triggering the cones equally. Another way to understand this is to consider a bright object, no matter how small. If the bright object has enough energy to trigger a cone, it will be seen. On the other hand a small dark object could not be noticed no matter how dark it is, if the surrounding background triggered all cones equally. Therefore minimum visual acuity is a function of intensity not size.²

For example, a star subtending only 0.056 seconds of arc can be seen while a dark spot is visible against a bright sky only if its diameter exceeds 14 seconds of arc. A dark line under the same conditions is visible only if it subtends 0.5 seconds of arc.²

Minimum separable acuity which is used in character recognition, and vernier acuity which is used for aligning dials and cross hairs, are two often used acuity figures in display work. A common limiting acuity figure among engineers is 1 minute of arc. This figure refers to the resolving power of the eye and not the eye's performance in a given task. Actually, objects subtending an angle of less than one minute of arc are visible. The figure of one arc minute is related to the visual task of character recognition where one must resolve gaps or spaces between line segments as, for example, the letters E & B. The eye must resolve lines and/or spaces of about 1/5 the character height in order to identify those characters. Tests show that spaces of approximately 1 minute of arc are the limit of visual acuity for this task.² The curve in Figure 20 shows probability of gap detection as a function of subtended visual angle.

When the task is changed from gap detection to alignment of a pointer with a dial mark (vernier acuity), the eye's acuity is appreciably better than one minute of arc. This is due to random positions of cones in the retina as portrayed in Figure 21.

If the image is moved slightly to the right, at least one cone (cone "a") will be activated. Because only a small part of the cone has to be illuminated to supply a nerve impulse, lateral movement smaller than a cone will be recognized. Under certain conditions of line length, contrast, and brightness, vernier acuity approaching one second of arc is attained. However a figure of 10 to 12 seconds of arc can be used as a minimum image width in displays calling for high placement accuracy and repeatability.²

In summary, the acuity of the eye is not the same as its resolving power. Acuity is primarily a function of brightness and other factors. Perhaps to a greater degree it is dependent on the visual task being performed.

* The cone is the smallest photo sensor in the eye and because it has only one neural connection to the brain; once the cone is triggered by light, even by a light source smaller than the cone, the brain can only interpret the size of the light source as being the size of the cone.

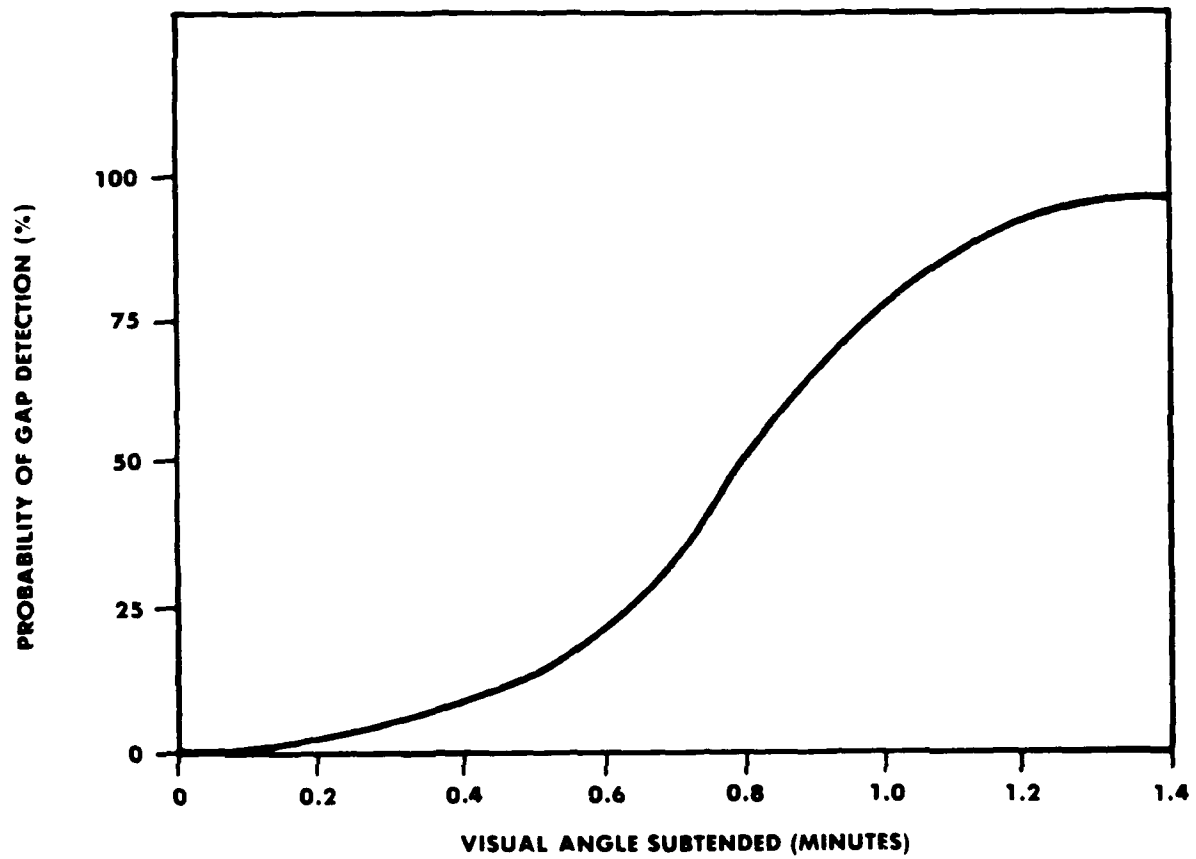


Figure 20. Probability of Gap Detection²

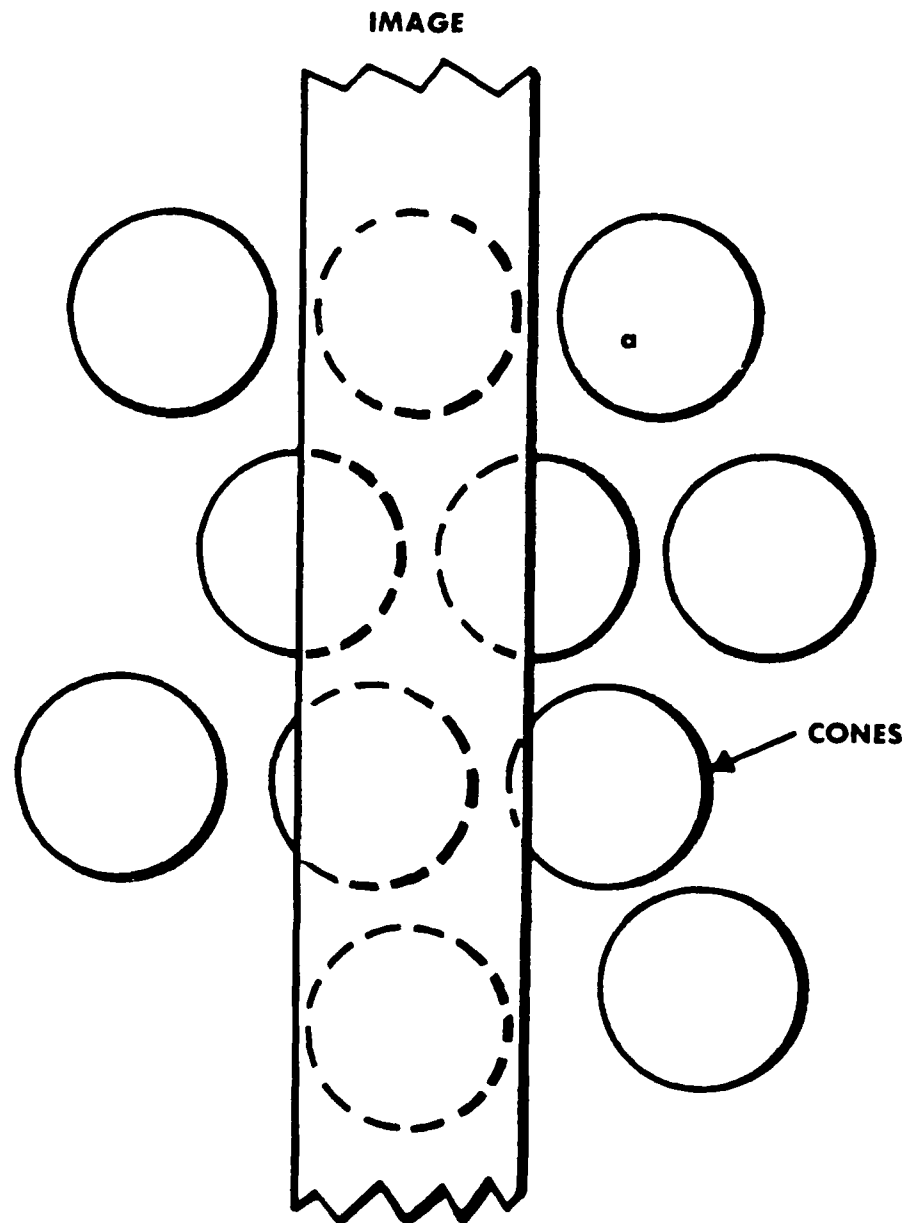


Figure 21. Image Focused on Visual Cones 2

Resolution of Displays

CRT resolution can be defined and measured in a number of ways such as:¹⁰

Spot diameter

Line width

Number of raster lines

Limiting TV response (resolution wedge)

Spatial frequency response or modulation transfer function

The variety of methods for measuring essentially the same property of displays have evolved from the various applications of the CRT.

Two significant factors used in determining CRT resolution are the current density of the electron beam when it strikes the phosphor, and the phosphor particle size and thickness, which limit resolution by scattering light. Phosphor resolution is improved by reducing screen thickness and particle size¹⁰ or by using thin-film transparent phosphors as described earlier in this report. Resolution improvement resulting from the use of thin film phosphors is obtained at the expense of phosphor brightness.¹⁰ Current CRT technology can produce a spot diameter or line width of .0008 inches for a 1 inch tube to .007 inches for a 25 inch CRT.¹⁰

Any statement of CRT resolution should include the operating potentials of the CRT gun and deflection electrodes. Where shades of gray are to be presented, resolution should be specified for both high and low brightness levels because resolution is a function of brightness in CRTs.¹⁰ Spot size and resolution vary as a function of the spots location on the screen; and therefore, a requirement for spot size uniformity should be specified to insure expected performance.¹⁰

It should be understood that a single spot on a CRT screen does not represent a simple "on and off" condition of brightness such as would be produced by a rectangular profile of current density. Luminance of a spot depends upon the distribution of current density in the electron beam. To a first approximation the luminance profile of a spot follows a Gaussian distribution of current density in the electron beam. To define the diameter of a spot, an arbitrary percentage of the central or maximum luminance is chosen. For most purposes, the diameter of the spot at the 50% luminance points defines its size. An approximate measurement of spot size can be made by observing it with a microscope equipped with a calibrated reticle.

Spot size can be measured accurately with a microscope photometer. The image is scanned through a slit which is thin compared to the spot being measured. The output of the photometer is observed on an oscilloscope whose horizontal sweep is calibrated in units of linear measure and is synchronized with the slit scanning motion. The spot luminance profile will appear on the scope and accurate spot-size measurements can be made at the appropriate luminance amplitude which is most often 50% of central luminance. The same measurement set-up can be used to drive an x-y chart recorder to produce a permanent record of the spot profile. The slit method can also be used to measure line width in the same manner as spot size.

Limiting TV-response is measured by observing the merge point on a resolution wedge of a television test pattern.

The shrinking-raster method measures resolution of a raster display in terms of the number of raster lines per unit length of picture height. This procedure displays a test raster with a known number of horizontal lines-usually 100. The vertical spacing of raster lines on the screen is varied by adjusting the vertical deflection gain. The spread of these lines is decreased by decreasing the vertical deflection gain until the line structure of the raster just disappears. The number of lines per vertical unit length is then computed by dividing 100 lines by the measured vertical dimension of the raster.

Modulation Transfer Function (MTF)

In recent years the concept of MTF as a useful measure of image quality has attracted increasing interest among display designers. The MTF measure is a transfer function that relates the size of image objects or spatial frequency at the input with the diminished contrast of the image at the output.

For example, assume the image at the input to be a set of parallel, vertical, thin, black lines separated by white spaces of the same width. The resolution of this image is the number of lines per unit length. When this image is scanned horizontally, the scanning beam converts the pattern to a number of lines per unit time thus the characteristic of this signal is called spatial frequency.

If the luminance contrast of the black and white lines of the input image is called M_{in} , the contrast of the output image will be some lower value M_{out} . The ratio of these contrasts is called the modulation transfer factor.

$$\text{Modulation Transfer Factor} = \frac{M_{out}}{M_{in}}$$

The plot of modulation transfer factor as a function of the useful range of spatial frequencies is the modulation transfer function (MTF) of the device or system under test. Generally the loss of output contrast (modulation) relative to input contrast (input modulation) increases with increasing frequency of image signal input.

The plot of modulation transfer factor for all spatial frequencies is the MTF shown in Figure 22. The MTF is a representation of imaging system capacity in the spatial domain and is based upon the theory of linear systems analysis and the mathematics of Fourier transformation.¹⁰

The fundamental importance of MTF lies in the fact that through the Fourier theorem any waveform (or image intensity distribution) may be broken down into a series of sine wave components each having a unique amplitude and phase relationship to each other.¹⁰

The paramount advantages of the MTF as a basis for image quality measurements are that it: (1) describes a large amount of what is generally considered to be critical to image evaluation, specifically the effect of spatial frequency on contrast or modulation, (2) can be used to describe in similar units the capabilities of the human observer using the display. Thus, it provides an analytical tool which permits the common evaluation of the display and the user in the same units, which are quantitative, well understood, and predictable, before the display hardware is built. The last advantage is economically important in that the acceptance of the MTF-based approach lets the designer simulate the effects of variety of design perturbations on the display system MTF and then estimate quantitatively the effect of the resultant MTF change on user performance.¹⁰

The reader interested in probing MTF in further depth is referred to an excellent exposition of the fundamental theory supporting this measurement, as well as clearly outlined practical measurement methods.¹⁵ The paper by Verona et al. is entitled "Direct Measurement of Cathode-Ray Tube (CRT)

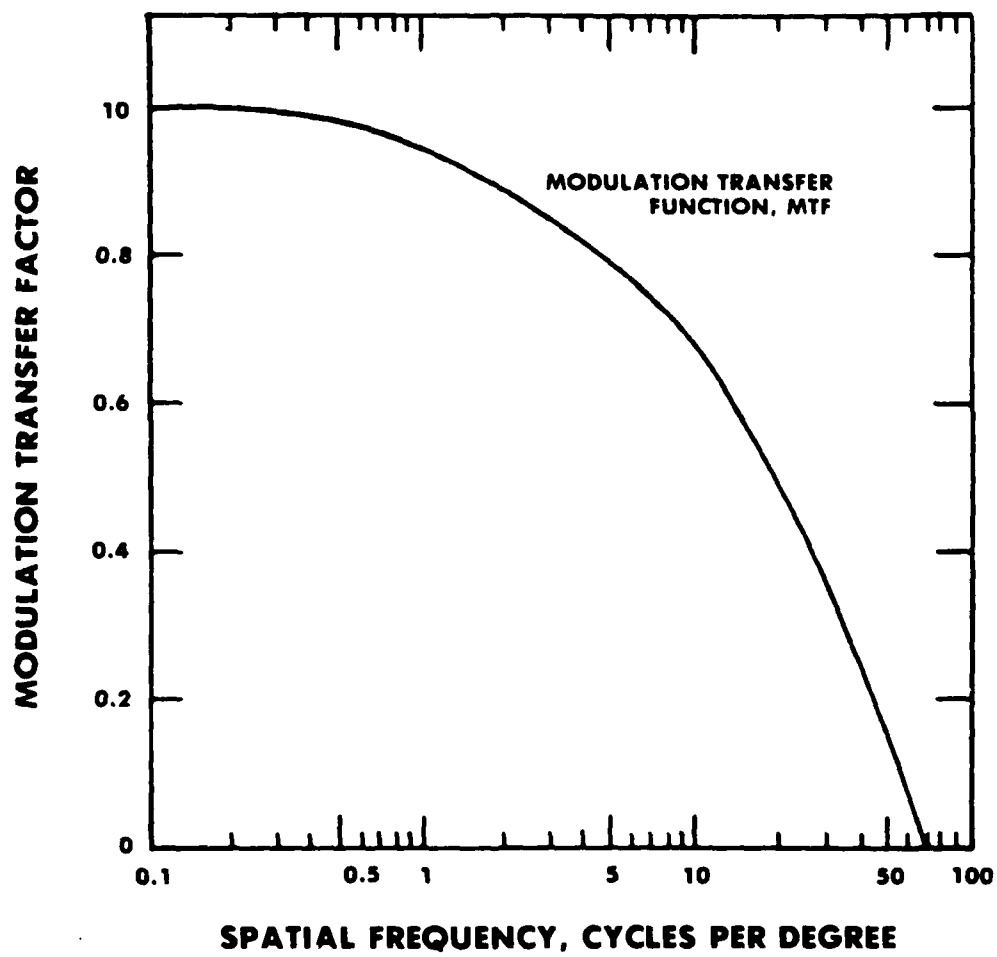


Figure 22. Modulation Transfer Function (MTF)¹⁰

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Image Quality". It is published in the Proceeding of Society of Photo-Optical Instrumentation, Volume 196, Measurement of Optical Radiations (1979).

APPLICATION OF CRT DISPLAYS

It would be impractical to list all the applications of CRTs. As tube technology advances more users for CRTs are found. The following is a brief discussion of four applications which are well known because of their importance in the historical development of CRT displays and because there are a large number of units in operation.

OSCILLOSCOPES

The first use of the cathode ray tube was as a laboratory device for the display and measurement of electrical waveforms. Cathode ray oscilloscopes were manufactured as commercial items for this purpose in advance of all other applications. The oscilloscope made possible graphic observation of both repetitive and transient electrical waveforms. Accurate amplitude measurements and ultra-precise time measurements of many orders of magnitude greater than previously possible were the main contributions of the laboratory CRT oscilloscope. With such a superb laboratory measuring device at hand the stage was set for the spectacular development of radar and television and many later technologically advanced devices such as electronic digital computers. Today the oscilloscope is a ubiquitous laboratory instrument used in such diverse fields as physics, chemistry, biology, and radio astronomy to mention a few. It is also a necessary tool for the trouble shooting and maintenance of electrical devices and systems.

RADAR

At the onset of World War II preliminary work with both radar and television was under way in the laboratory. The war quickly reversed what would have been the normal priority and placed emphasis on the development of radar instead of television. The CRT in conjunction with electronic timing circuitry made possible the accurate measurement of the transit time of an r.f. pulse in its travel from antenna to target and return. Propagation velocity of the pulse is 186,000 miles/second, making it necessary to measure time in micro seconds in order to accomplish accurate range measurements.

As development of this application was pursued, the CRT was also used as a plan position indicator (PPI). In this mode the tube presented a map-like, plan view of the earth or sky being scanned by the rotating radar antenna.

During the war, technical development of radar was accelerated greatly increasing its performance and scope of application. During the latter part of the war the United States Eighth Air Force was able to bomb strategic targets through clouds. Radar, used effectively as an anti-submarine weapon, contributed significantly to curtailing German submarine attacks on Allied shipping.

At the end of hostilities radar technology was applied to the control of commercial air traffic. It has been continuously refined since then and one could safely say that commercial aviation would not exist in its present state without the concurrent development and use of radar in air traffic control and all-weather flying.

TELEVISION

Without doubt, the most widely known and used CRT display is the "picture tube" of the ubiquitous television receiver. There is hardly a person today who does not watch a TV receiver at least part of

each day. There is, in fact, a large segment of our population who cannot remember ever being without the presence of a television set and would find it hard to imagine what life would be like without TV.

While crude mechanical means of transmitting pictures were demonstrated before the 1900's it wasn't until the 1920's that the concept of an all electronic TV was pursued. The all electronic TV emerged from the lab in 1933 and test broadcasts from the Empire State Building in New York City began in June of 1936.

The commercial TV era began in September 1946 when the first post war TV sets went on sale and the commercial television industry took off and has been growing ever since. On October 31, 1953 the first hour long program in color was broadcast and today television is an integral part of American culture.

INFORMATION DISPLAYS

The advent of the electronic digital computer with its ultra high-speed calculating and processing ability created a need for input-output devices to control the computer and to display the results of its data processing and computations. It was a ready-made application for the CRT display. Because the CRT is a high speed device, it enables the operator to read the alpha-numeric symbology being displayed and to interact with it by operating the typewriter keyboard. The keyboard is an input device to the computer allowing an iterative process to take place between the CRT's display to the operator and the operator's response via the keyboard.

The computer terminal with its CRT display and typewriter keyboard is quickly becoming a standard piece of furniture in the modern office. The CRT computer terminal may become as standard an item in the work place as TV sets are a standard item in the American home.

SUMMARY

Why has the CRT survived the on-rush of solid state technology? It has not only survived but holds a commanding lead in the visual display field.

For high-resolution high-speed applications the CRT is superior to other display devices. Moreover, its excellent resolution makes it capable of producing dynamic imagery of sufficient quality to satisfy the human eye¹⁰.

Scanning in a CRT is simple but versatile enough to accommodate raster scan, stroke scan, or random scan. Sometimes it can accommodate two deflection modes by time-sharing, giving the appearance of simultaneous presentation.

Cathode Ray Tubes furnish bright imagery in monochrome or color. The tube has long life, is reliable and relatively inexpensive¹⁰.

The chief disadvantage of the CRT is that its depth is comparable to its longest surface dimension. This has often spurred intensive development activity, by research engineers, to increase the performance of flat panel displays and to develop a superior replacement for the vacuum tube CRT especially with respect to its deep dimension.

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